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THE ASSESSMENT OF THE COLORIMETRIC PROPERTIES OF LIGHT SOURCES FOR USE IN TELEVISION SCENE LIGHTING

E.W. Taylor, M.A. (Cantab.), C.Eng., M.I.E.E.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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Summary

An account is given of the Television Consistency Index method of assessing the colorimetric properties of light sources for use in television scene lighting. Theoretical limits have been determined within which this Index may be used as a general description of lamp performance, bearing in mind the inevitable differences in spectral analysis characteristics (spectral sensitivities) which exist between one practical colour television camera and another. Practical comparisons between displayed colour television scenes are described, in which the original scenes were illuminated by different lamps. The results of these tests are used to examine the validity of the Television Consistency Index, both in absolute terms and in relation to the alternative use of the General Colour Rendering Index in this context.

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M. E. B. Moffat

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

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1. INTRODUCTION

The problem of assessing the colorimetric properties of light sources for use in television (or indeed film) scene lighting is not new. In the past, however, the choice of artificial light source has been rather restricted, and has in the main consisted of incandescent sources running at various temperatures. In such cases the spectral power distribution corresponds, to a reasonable degree of approximation, to a Planckian or "full radiator", and the temperature of that radiator ("colour temperature") has provided an adequate description of the source. Where the source has not been strictly Planckian (e.g. daylight) the spectral power distribution has still been reasonably continuous and the concept of "correlated colour temperature" has been invoked. Colour filters have become available to "raise" or "lower" the colour temperature of a source, and direct-reading meters have been developed which give an indication of colour temperature on a suitable display. Both of these aids to the lighting engineer rely on the continuous nature of the spectral power distribution of an incandescent source (or daylight) and can give very misleading results when used to correct the light from, or assess the parameters of, a discharge lamp whose spectral power distribution is concentrated in relatively few bands. This was not of great importance when discharge lamps having spectral power distributions broad enough to make their use as scene illuminants worth considering were not common: such few lamps as might be suitable for this purpose could be treated on an "ad hoc" basis on each occasion that they were encountered. However, the advent of a relatively large number of discharge lamps (both of the high-intensity discharge and the fluorescent types), which have become common sources both for interior and exterior lighting, has brought with it the need for a new formal system of lamp categorization to replace the inaccurate "colour temperature" method. The problem has already been tackled in the field of direct observation of coloured objects by the specification of the "Colour Rendering Index", R_a. It was felt that the problems met with in the field of colour reproduction were sufficiently different from those of direct observation to warrant an investigation into the provision of a separate Index (or Indices) for such purposes. This Report is concerned with the investigations on this subject carried out by the committee members listed in Section 7.

The programme of work under which this investigation was carried out was as follows:-

(1) To devise and recommend a "working model" of the television colour reproduction process, capable of mathematical description so that it can be incorporated in computer software and thus be capable of experimental use in the laboratory.

(2) The purpose of the working model is to enable the colorimetric effect of changing the lamp used for illuminating the scene being reproduced to be evaluated, as far as possible without including the imperfections of the reproducing process in this evaluation.

(3) As far as possible the working model should be of general validity so that new or improved data can be incorporated without the need for re-writing the recommended procedure.

(4) Attention was called to the CIELUV 76 and CIELAB 76 colour-difference formulae.

Although the use of "mixed lighting" techniques (the use of different types of lamp to illuminate the same scene), and the associated problem of choosing lamp filters so that colorimetric differences (e.g. coloured shadows) do not then appear in the reproduced picture, are often encountered in practice, this subject has not been included in the present work.

Bearing in mind the programme of work outlined above, and specifically that Item 2 referred to differences of colour reproduction obtained when using first the lamp under test, and subsequently a "reference" lamp, for colour television scene illumination, the Television Working Party decided to investigate the Television Consistency Index[1, 2] as a method of satisfying these requirements. This method (see Section 2) involves the calculation of the reproduced chromaticity and luminance of each of a number of test colours under the two conditions of scene illumination followed by a numerical assessment of the difference in reproduction using a colour-difference formula. The method is thus quite general in character, satisfying Item 3 of the programme of work. Specific values have to be attributed to all the parameters used in defining the colour television process, as well as to such items as the test colour set and the spectral power distribution of the reference illuminant (or illuminants), in order to define a

"general" Index (see Appendix 1), but "special" Indices can be envisaged to take account of any departures from these defined general conditions that may be considered necessary. This procedure closely follows the principles already laid down for the Colour Rendering Index (R_a) and indeed the concept of the Television Consistency Index is modelled on this earlier formulation. However, whilst the calculation of the Colour Rendering Index is carried out using a reference illuminant of similar chromaticity to that of the lamp under consideration, only two reference illuminants are used in the case of the Television Consistency Index: these are chosen to represent conventional incandescent ("tungsten") studio lighting on the one hand, and natural daylight on the other (see Section 2.2). Furthermore, in line with Item 4 above, the CIELUV 76 colour-difference formula has been adopted instead of the 1964 "uniform colour space" formulation. The CIELAB formula was not used as it was thought to be inappropriate to an additive colour reproduction process (in the sense that a chromaticity diagram is not associated with it) and, further, that colour-difference values using a white point that approximates to D_{65}, such as is the case in television displays, are similar for both the CIELUV 76 and CIELAB 76 formulae.

The Television Consistency Index uses the principle that a lamp would be considered suitable for colour television if it gave consistency of colour reproduction (i.e. little colorimetric change) when the scene was illuminated first by the lamp under test, and then by one or the other of two "reference illuminants" which represented present-day practice in studio and outside-broadcast television lighting. A difficulty in using such a method is that the effect of using different light sources for television scene illumination is influenced to some extent by other parameters of the television system, of which the most important is the set of colour analysis characteristics (spectral sensitivities) of the camera which is in use. Index values appropriate to one set of camera characteristics will differ somewhat from corresponding values (i.e. referring to the same lamps) using another set of characteristics. The question then arises: is the influence of the camera analysis characteristics rather weak, so that tests on the lamps conducted using one camera may be directly applied when another camera is used; or, alternatively, do the Index values depend so strongly on the camera analysis characteristics that the Index values obtained using one camera give no indication of the values which would be obtained using another camera? In the first case, a particular light source would affect the colorimetric behaviour of different makes and types of camera in a reasonably similar manner; furthermore, a single "reference" set of camera analysis characteristics[1] could be used in the calculation of the Television Consistency Index values, making it possible for these values to be calculated without prior knowledge of particular camera characteristics. In the second case it would be necessary to take account of the make and type of camera when choosing light sources for television studio lighting, and the use of the Television Consistency Index would be confined to the examination of the effect of using different light sources in conjunction with particular cameras. One of the principal objectives has therefore been to assess the degree to which camera analysis characteristics affect Television Consistency Index values.

Two principal methods of analysis have been used:-

(a) Regression analysis

(b) Rank order difference analysis

In both cases the analysis has been in terms of comparisons between two sets of Index values, each involving the same lamp spectral power distributions (Section 2.4) but differing in the camera analysis characteristics used in the calculations (Section 2.3). Regression analysis (see Section 3.1) will indicate the degree of certainty with which the Index values obtained using one camera can be used to predict values which would be obtained using another camera. Using regression analysis, upper and lower bounds can be calculated, within which the predicted value will fall with a given probability. An important aspect of the use of the Television Consistency Index, however, is the ability to order or "rank" a number of lamps in terms of their suitability for use in television scene lighting. This aspect is of particular importance to lamp users who may in future be involved in making decisions on which one of a number of lamps to use in a studio. The answer to the question as to whether the influence of the camera does or does not affect the general validity of the use of the Television Consistency Index now hinges on whether the rank orders of lamp suitability, in terms of Television Consistency Index value, do or do not differ significantly from camera to camera. Rank order analysis, as discussed in Section 3.2 of this Report, provides a method of assessing the significance of these rank order differences.

A series of field trials was undertaken to establish whether the theoretical results described in Sections 2 and 3 were borne out in practice. Three sets of trials were carried out, two using a tungsten lamp as reference illumination to give a standard reference picture and one using one of the test lamps, which had a spectral power distribution similar to that of daylight, as a reference (although this lamp was not entirely satisfactory for the purpose). All the field trials used a set of eight test lamps whose colour rendering

varied from very good to poor (at least when judged by their General Colour Rendering Index values). The first Field Trial used a test scene in which two people were seated in front of a "pop art" background. A total of 37 observers made judgments on the colorimetric consistency of reproduction. Two modes of viewing were employed, using alternate picture presentation in one case, and a split-screen technique in the other. The second Field Trial used an Edwardian drawing room scene containing a seated figure. A total of 27 observers made judgments of consistency using only the alternate form of presentation. The third Field Trial used the same material as the first, but the video tapes were re-edited so that the picture obtained when using the "daylight-like" test lamp (see above) was taken as the reference. In this case 18 observers took part. The detailed results of all three field trials are given in Appendix 2, and these results are discussed in Section 4.

2. CALCULATION OF TELEVISION CONSISTENCY INDEX VALUES

2.1 Introduction

Following the procedure used in deriving the CIE General Colour Rendering Index, it is proposed that an average Index value is taken over a number of test colours representing the complete gamut of scene colours that can be reproduced by the television system. Because of the particular importance attached to the correct reproduction of skin tones, a second average is taken over a number of skin-tone test colours to give a "skin-tone" index. Furthermore, because the presence of one inconsistently reproduced colour (or perhaps a few such colours) in an otherwise consistently reproduced scene would have an adverse subjective effect much greater than the overall average Index would suggest, the "worst" (i.e. numerically lowest) Index value out of the Indices obtained for the individual test colours is also quoted, together with the identifying number of the particular test colour concerned. These considerations suggest that the Television Consistency Index should be expressed as four numbers:

(i) Overall Index.
(ii) Skin-tone Index.
(iii) Worst Index.
(iv) Number of the test colour giving the worst Index.

Such a presentation is however rather cumbersome, and it may be possible to combine the first three parameters into one quantity. In fact, although skin-tone reproduction is very important, skin-tone Indices are numerically higher than the average over all test colours, because of the relatively low saturation of skin-tone test colours. Skin-tone Indices also show good correlation with the overall Indices. Thus it may not be necessary to take account of specific skin-tone Index values: a lamp showing a good overall value is very unlikely to give poor skin-tone reproduction. (Note, however, that the converse is not necessarily true: lamps exist which give good skin-tone reproduction but poor reproduction of other colours).

2.2 Formulation

In the calculation of the Television Consistency Index a set of test colours is assumed to be reproduced by a television system under two conditions: first with the test colours illuminated by the lamp under test, as shown on the right of Fig. 1, and then with the colours illuminated by a "reference" illuminant, as shown on the left of the Figure. In each case the television system is balanced (i.e. the relative gains of the colour separation channels are adjusted) so that achromatic scene objects are reproduced with the chromaticity of the display white point. Following the procedure proposed for the calculation of the CIE Colour Rendering Index from the chromaticities and luminance values of directly-illuminated test colours (Fig. 1)[3], and using the recommendations made by the CIE in 1976[4] (see Appendix 1) the results of the two conditions of reproduction are compared, colour by colour. The Television Consistency Index for the i^{th} test colour (R_{ti}) is then given (still following the Colour Rendering Index procedure) by the expression:

$$R_{ti} = 100 - 4.6\ \Delta E^*_{uv,i} \qquad (1)$$

where $\Delta E^*_{uv,i}$ is the colour difference for the i^{th} test colour, as given by the CIELUV 1976 colour difference formula. (Note that the constant "4.6" is carried over from the original Colour Rendering Index formula, which was based on the CIE 1960 Uniform Chromaticity Scale and the 1964 Uniform Colour Space. It has been suggested[12] that this value may not be appropriate when the CIELUV 76 colour difference formulation is used. In any case, it may be appropriate to modify this value when greater experience has been gained in the behaviour of the Television Consistency Index, as discussed in Section 5.) Following the calculation of the Television Consistency Index for each test colour, averages are taken over certain test colour sets as described in Section 2.3.

It may be noted that in some earlier work the value of $\Delta E^*_{uv,i}$ (see Eqn. 1) was obtained using the original (1964 U*V*W*) colour difference formula[5]. Consistency Index values calculated in this way are very similar to those calculated using the CIELUV 1976 formula, and in general the same conclusions may be drawn from Index data obtained using either formula.

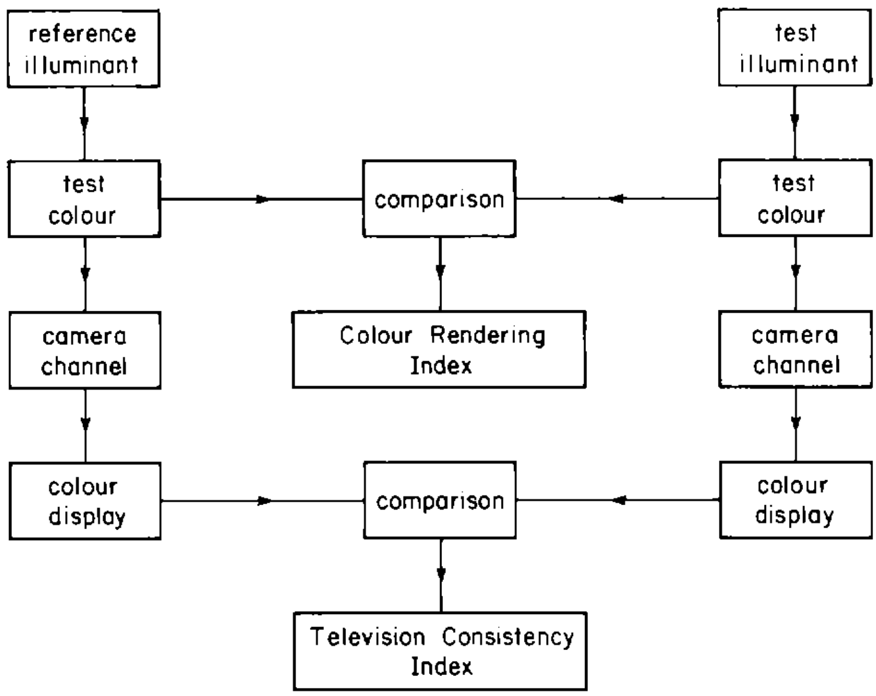

Fig. 1
Block diagram showing method of calculation of the Television Consistency Index.

In the foreseeable future, tungsten lighting will continue to be used very frequently in studio applications, and it is obvious that daylight will be the normal illumination for the majority of outside events. The purpose of the Television Consistency Index therefore becomes the assessment of lamps for lighting television scenes that will most likely be intercut with (or at least be viewed very shortly before or after) other scenes which have been illuminated with either a tungsten source or with daylight. Two reference illuminants have therefore been selected: P_{3000} (a full radiator at a temperature of 3000K) to represent studio working using tungsten illumination, and D_{65} (reconstituted daylight having a correlated colour temperature of approximately 6500K) to represent outside broadcast operations. Consistency Index calculations are carried out using each reference illuminant in turn. If one of the resulting Index values has a value high enough to ensure that lamp performance is satisfactory, then the lamp may be categorized either "studio compatible for television" or "daylight compatible for television" depending on which reference illuminant gives rise to this high-value Index. (It may be noted that the actual Index value above which lamp performance may be deemed satisfactory has not yet been determined with precision: this aspect is discussed in Section 5.) This assessment is intended to replace the use of correlated colour temperature as a description of lamp colorimetric performance in television scene lighting applications.

2.3 System parameters

Tests have shown that very good correlation exists between Index values calculated for the same lamps using different test colour sets (see Section 3.5) provided that the sets used explore the colour television colour gamut adequately. Coincidentally, the degree of correlation between values obtained using each of three test-colour sets (the Macbeth Color Checker, the "EBU" set and the "original" set described in Section 3.5) is the same as the correlation obtained using different camera analysis characteristics (see Section 3.1). The absolute values, or "scale", of the calculated Indices do however depend on the test colour set and so it is necessary to specify a particular set when putting forward parameters for a "general" Index. Most of the theoretical work has been based on an "overall" index value taken over 25 test colours which include the eight BBC desaturated colours, the eight BBC skin tones, the eight CIE desaturated colours[3] and the CIE skin tone[3].

The television system parameters used in the calculation of Index values are, as far as possible, typical of current practice. An overall transfer characteristic ("gamma") of 1.2, and a reference "white" of 60% reflectance, are used. Linear matrixing is assumed to be applied to the colour-separation signals, the coefficients being chosen to give best colorimetric performance using the two reference illuminants. Emphasis has been placed on the use of the "extended-red" category of colour television cameras (which are not subject to a restriction of the response of the red channel to wavelengths below about 650 nm, caused by the characteristics of some lead-oxide camera tubes), as this category now largely represents present-day practice in camera design. Eight sets of such extended-red characteristics, derived from measurements of colour television cameras of broadcast quality, have been used. In each case the camera matrix coefficients used in the calculation were those

used operationally. All the cameras were three-tube and of the conventional RGB type except one, which was of the "wide-green" or RYB type. The signal processing of this type of camera is very similar to that of a four-tube ("YRGB") camera. The picture was assumed to be displayed using the European Broadcasting Union (EBU) set of display phosphor chromaticities[10].

Television Consistency Index values have also been calculated using an extended-red "reference" analysis, the purpose of which would be to enable a "general" Consistency Index to be calculated without prior knowledge of any particular camera analysis characteristics. These reference characteristics, which are shown in Fig. 2, were derived by considering the positive lobes of the theoretically "ideal" analysis characteristics required for the EBU set of display phosphor chromaticities, without reference to any practical camera. They were used in conjunction with camera matrix coefficients calculated for the EBU display chromaticities and given by the relationship:

$$\begin{bmatrix} R_m \\ G_m \\ B_m \end{bmatrix} = \begin{bmatrix} 1.138 & -0.175 & 0.037 \\ -0.112 & 1.151 & -0.039 \\ 0.000 & -0.091 & 1.091 \end{bmatrix} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \qquad (2)$$

where R_m, G_m and B_m are the red, green and blue matrixed colour-camera signals, and R_c, G_c and B_c are the corresponding camera-tube signals. It may be noted that NTSC (or any other) phosphor chromaticities, with the appropriate 3×3 matrix, would have been equally valid.

Work was also carried out using three sets of practical "narrow-red" (i.e. subject to the wavelength restriction mentioned above) camera analysis characteristics, together with a corresponding narrow-red reference analysis.

2.4 Lamp spectral power distributions

Two principal sets of lamp spectral power distributions (spd's) have been used to derive the Index values used in the tests. It is hoped that these spd's give a good representation of lamps likely to be encountered in practice. Both of these spd sets have been derived by J.J. Opstelten. In the first place, 63 lamp spd's have been derived by combining the spectral power distributions of various phosphors in the case of fluorescent lamps, or additives in the case of high-intensity discharge lamps. As the lamps represented by those spectral power distributions have not been constructed physically, the spectral power distributions must be regarded as hypothetical and only an approximation to the actual spectral power distributions that would be obtained by the given combinations of radiating components. This is particularly true in the case of discharge lamps where the spectral power distributions of the additives are not mutually independent. Nevertheless the 63 hypothetical spectral power distributions may be regarded as typical of a large range of discharge lamps. In calculating the spectral power distributions of these lamps, they were arranged to be in sub-sets or "lamp families". Each family consists of seven members: the chromaticities of four members correspond to full (Planckian) radiators at temperatures (or in other words have "colour temperatures") of 2600K, 3000K, 3500K and 4200K, and the chromaticities of the other three members correspond to reconstituted daylight with correlated colour temperatures of 5000K, 6500K and 8000K (Fig. 3). There are nine families in all. In any one family (with one exception) the constituents of the lamp (i.e. the phosphors or additives within it) are the

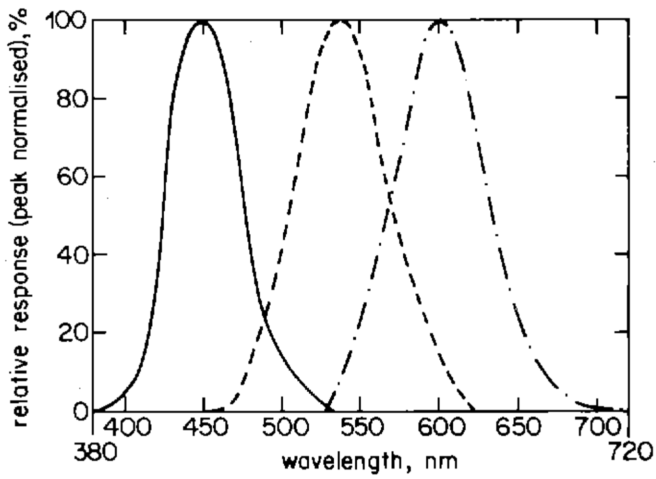

Fig. 2 - Extended-red reference analysis.

——— blue channel
– – – – green channel
—·— red channel

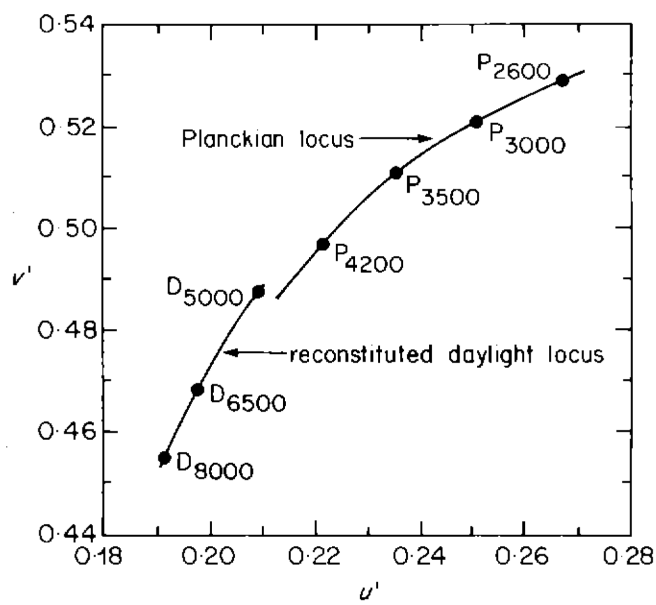

Fig. 3 - Chromaticities for first (hypothetical) set of lamp spectral power distributions.

same, but the proportions of these constituents are varied from lamp to lamp to give the required chromaticities. The exceptional lamp family did not represent either a fluorescent or a high-intensity discharge lamp, but consisted of the actual full-radiator or reconstituted daylight spectral power distributions themselves. The 63 spectral power distributions could also be grouped in a different way, so that each sub-set consisted of "lamps" of identical chromaticity, but of different spectral content. There were seven such groups, each having nine members. The second set of lamp spd's consists of the measured characteristics of 66 practical lamps, again including both fluorescent and high-intensity discharge lamps. In this case no exact grouping in terms of lamp chromaticity is possible, but the lamps have been categorised into ten families of restricted chromaticity range. (One family is exceptional in that it includes all lamps of colour temperature greater than 6450K).

3. THEORETICAL EXAMINATION OF PROPERTIES OF THE TELEVISION CONSISTENCY INDEX

3.1 Regression analysis of Television Consistency Index data

Two Consistency Index values may be calculated in which all the parameters entering into the calculation are the same, except for one (for example, the camera analysis characteristics). These two values may then be regarded as the Cartesian co-ordinates of a point, which may be plotted on a graph. If this process if repeated, using the different lamp spectral power distributions in each case, a "scatter diagram" is obtained (Fig. 4) which portrays the relationship between Indices calculated using one set of camera analysis characteristics and those calculated using another set of analysis characteristics. The scatter diagram shows that there is a strong tendency for the two sets of Index values to be related, but that there is an element of randomness in this relationship, and so it is not perfectly functional. This state of affairs is not surprising, as there is an element common to both sets of Index values (the lamp spectral power distributions) which would tend to lead to similarities in the Index values obtained for each lamp, and there is also an element which differs between one set of Index values and the other (the camera analysis characteristics) which could tend to produce differences in the Index values obtained for particular lamps. The result of such analysis is the derivation of the equation of a (straight) "line of best prediction" of Index values which would be obtained under the conditions shown for the y-axis of the scatter diagram, using as a basis for such predictions the corresponding values obtained using the x-axis conditions. Such predictions are subject to an "uncertainty" value ($\pm\eta$), such that there is a 95% probability that the predicted value will be within this range (this criterion is widely regarded as a reasonable measure of significance, and is felt to be appropriate in the present case). This uncertainty can be represented on the scatter diagram by two further straight lines having the same gradient as the line of best prediction, but being separated from it in the y-direction by $\pm\eta$ in the cases of the upper and lower lines respectively.

If individual predictions of Consistency Index value are subject to an uncertainty of $\pm\eta$, as described above, then it can be shown that a difference between two such predicted Index values which is less than 1.16η does not differ significantly from zero. Two lamps whose predicted Index values differ by less than this amount should therefore be regarded as being the same in respect of their suitability for television scene lighting.

Inspection of Fig. 4 shows that although the points in the scatter diagram are indeed contained within the limit lines as predicted by statistical theory, the lines do not represent the actual distribution of the points very precisely, especially for high Index values. Another set of limit lines can be derived by carrying out regression analysis not on the Consistency Index values, but on the logarithms of the colour differences (see Equation 1) from which they are formed. This process is here termed "non-linear" regression analysis. When converted back into Consistency Index terms, these limit lines diverge from the (100,100) point on the scatter diagram on each side of the line of best

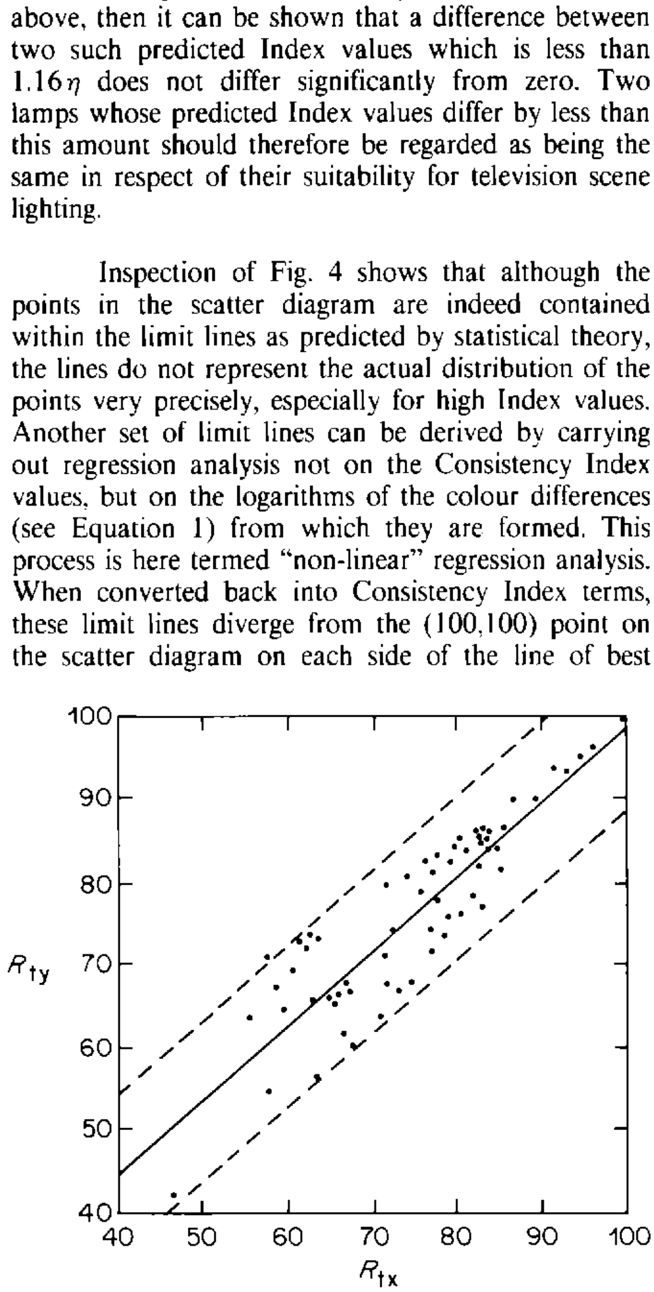

Fig. 4 - Illustration of scatter diagram, showing results of linear regression analysis.

——— Line of best prediction.
– – – – Limit lines showing uncertainty of prediction.

R_{tx} and R_{ty} are Television Consistency Index values calculated using, for example, two different sets of camera analysis characteristics.

prediction, as shown in Fig. 5. The uncertainty value is proportional to the amount by which the predicted Index value differs from one hundred. In this case the limit lines correctly represent the distribution of points on the scatter diagram for high Index values but give rather large uncertainty values for lower Index values.

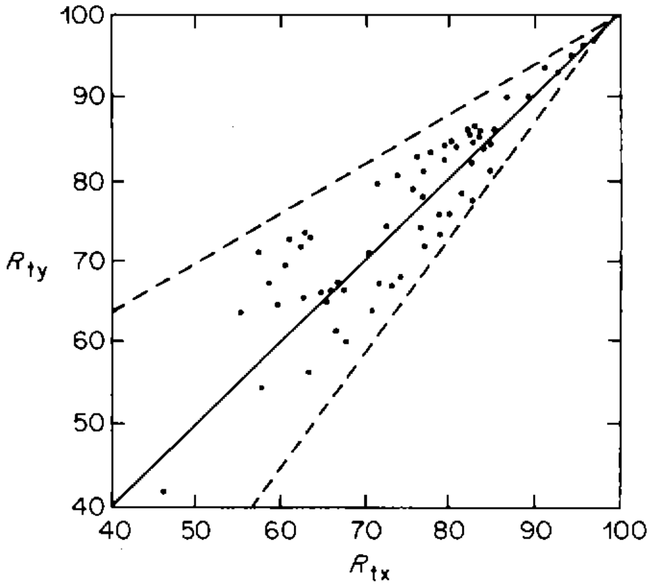

Fig. 5 - Illustration of scatter diagram, showing results of logarithmic regression analysis.

——— Line of best prediction.
– – – – Limit lines showing uncertainty of prediction.
R_{tx} and R_{ty} : see Fig. 4.

Since both sets of limit lines, as shown in Figs. 4 and 5, represent the statistical distribution of points on the scatter diagram, the two forms of expressing this distribution may be combined in such a way that the actual uncertainty value that is adopted is the lower of the values shown in Fig. 4 or Fig. 5. The resulting limit lines will be as shown in Fig. 6. The uncertainty value is independent of low Consistency Index value and in this case is equal to the value obtained from the linear regression analysis. The transition between the two forms of uncertainty value occurs at the Index value for which both methods of regression analysis give the same uncertainty value.

The value of Consistency Index obtained for a particular lamp in the case of one practical camera can be used directly as a prediction of the Index value for the same lamp that would be obtained for another practical camera. If R_t is this predicted value, then it would be subject to the following limits:-

$$\begin{array}{lll} \text{uncertainty} = \pm 7 & R_t \leqslant 75 \\ \text{uncertainty} = \pm 0.28\,(100 - R_t) & R_t > 75 \end{array} \qquad (3)$$

Differences between two such predicted Consistency Index values are subject to an uncertainty which may be stated as:-

$$\begin{array}{ll} \text{uncertainty} & \\ \text{of difference} = 8 & R_t \leqslant 75 \\ \text{uncertainty} & \\ \text{of difference} = 0.32\,(100 - R_t) & R_t > 75 \end{array} \qquad (4)$$

Here R_t is taken as the mean of the two Index values. It may be noted that these limits have been derived from data involving all eight practical extended-red cameras, both reference illuminants and both lamp spd sets (7224 data points). The parameters given in Equation 3 and 4 therefore disagree in detail with those that can be derived from Figs. 4 - 6, which refer only to one camera comparison, one reference illuminant and one lamp spd set.

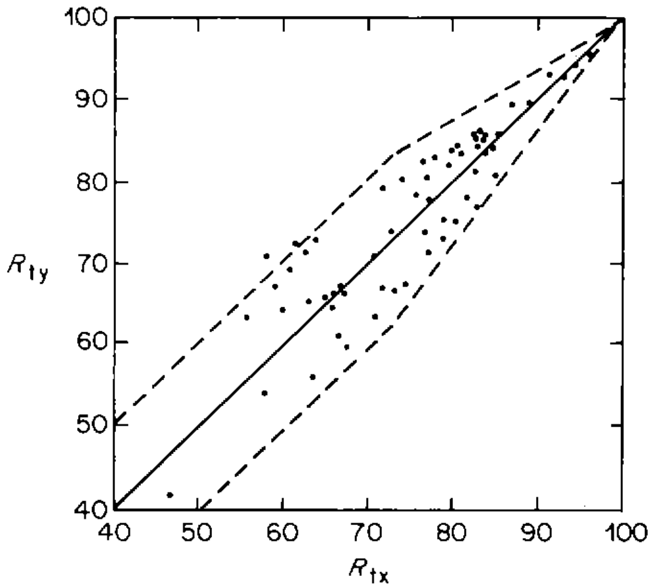

Fig. 6 - Illustration of scatter diagram, showing combined results of linear and logarithmic regression analyses.

——— Line of best prediction.
– – – – Limit lines showing uncertainty of prediction.
R_{tx} and R_{ty} : see Fig. 4.

3.2 Rank order difference analysis of Television Consistency Index data

Consistency Index values obtained for a number of lamps can be used to "rank" the lamps in order of merit as far as their suitability for television scene lighting is concerned. The rank order obtained in this way may alter if the camera analysis characteristics used in the calculation of the index values are changed. Rank order difference analysis[6,7] is intended to measure the confidence with which the rank order obtained using one set of camera characteristics can be used to predict the order that would be obtained using another set of characteristics.

As in the case of regression analysis (see Section 3.1), rank order difference analysis is carried out between two sets of Consistency Index values, each set referring to the same lamp spectral power

distributions and reference illuminant, but differing in the camera analysis characteristics used in the calculation. Rank orders are assigned to each lamp, using in turn the two sets of Consistency Index values. For each lamp, the numerical difference in the two orders obtained in this way is taken, and the square of this value is calculated. The sum of these squared values is then taken, over the complete set of lamps (or in other words over all the items in the rank orders), to give the difference coefficient Δ. Thus if a, b, c, d... and p, q, r, s... are the rank orders under comparison (the lamps themselves being in the same position in each tabulation of rank order) then:

$$\Delta = (a-p)^2 + (b-q)^2 + (c-r)^2 + (d-s)^2 + ... \qquad (5)$$

Except in the case of "tied" rank orders (when two or more lamps have the same Consistency Index value), difference coefficient values are always even integers. The value zero occurs when the two rank orders are the same, and the greatest possible value occurs when one rank order is the reverse of the other. All the possible values of Δ between these two extremes occur in principle at least once, but the number of rank order comparisons corresponding to each value of Δ depends in a rather irregular way on this value. The cumulative distribution of the individual values of Δ has been tabulated for different numbers of items in each rank order, and from this the probability of a difference coefficient being less than or equal to its actual value, assuming that the rank orders themselves are mutually random, can be derived. Statistical analysis then enables a limiting value of difference coefficient to be chosen, such that if the actual difference coefficient given by the rank order difference analysis is less than this limiting value, then there is only a probability of 0.05 or less that the two rank orders under consideration would have been as similar to each other, as is in fact found to be the case, purely by chance. In this case one rank order may be regarded as a reliable agent for predicting the other. If this criterion is not satisfied, then the two rank orders are described as being "significantly different". Comparisons between all possible pairs of Television Consistency Index data sets, involving all eight extended-red practical cameras as well as the extended-red reference analysis, then give an overall view of the ability to predict rank orders appropriate to one camera analysis from results found using another such analysis.

It should be noted that, when carrying out the rank order difference analysis, the "uncertainty" of Consistency Index value derived from regression analysis (see Section 3) is disregarded. Only if two Index values were the same (to two decimal places) were the rank orders of the two lamps regarded as the same. This procedure was adopted because this type of analysis is not well suited to situations in which a large number of such "tied" rank orders are present.

The implication of the "5% probability criterion" used to judge whether or not two rank orders are or are not significantly different should perhaps be examined. This is in fact the same criterion as was used in regression analysis to decide on the uncertainty limits of Consistency Index value: as stated before, this limit is widely regarded as a "reasonable" criterion of significance. Because there are a large number of possible rank orders (the factorial of the number of items being ranked), the number of rank order differences considered insignificant (5% of the total number of possible rank orders) can still be considerable. Thus "insignificance" of rank order difference must not be taken as implying zero or even "very little" difference. Instead, the difference is less than can reasonably be expected purely by chance, and is therefore due (as discussed in the context of regression analysis) to the predominant influence of the element common to both sets of Index values (the lamp spectral power distributions) as compared with the element differing between one set of Index values and the other (the camera analysis characteristics).

Rank order difference analysis has been carried out over both of the complete sets of lamp spectral power distributions ("hypothetical" lamps and "practical" lamps) and also over the individual sub-sets or "families" in each of these sets. In both overall rank order comparisons, it was found that the difference coefficient never exceeded or even approached the value corresponding to the 5% probability criterion (indeed, the highest difference coefficient corresponded to a probability of only about 0.01% that the two rank orders would have been as similar to each other as was in fact found, purely by chance). Thus it can be claimed that a rank order obtained over either complete set of spectral power distributions using one extended-red camera analysis may reasonably be used to predict the rank order that would be obtained using another such camera analysis. More specifically, this implies that Index values derived using the extended-red reference analysis provide a basis for ranking lamps in the order of merit that would be obtained using practical extended-red cameras.

Attention may now be turned to the rank order difference analysis carried out within the individual sub-groups or "lamp families" into which the two sets of spectral power distributions were divided (see Section 2). Considering the seven "identical chromaticity" sub-sets within the 63 hypothetical spectral power distributions, and the ten sub-sets of restricted chromaticity range, within the 66 practical spectral power distributions, only one of

these sub-sets (five practical high-intensity discharge lamps in the correlated colour temperature range 2550K - 3150K) showed any significant rank order differences, despite the fact that uncertainty of Consistency Index value was ignored in this analysis. If this uncertainty is taken into account, the rank orders obtained using either of the practical cameras involved in this disagreement were compatible with the rank order obtained using the extended-red reference analysis. It therefore seems reasonable to infer that Consistency Index values calculated using the reference analysis provide a sound basis for deriving a rank order of a number of lamps, which will be applicable to all practical cameras of broadcast quality, when lamps of similar chromaticity are being compared.

Rank order difference analysis has also been carried out over the nine original sub-sets or "lamp families" of the 63 hypothetical lamp spectral power distributions, in which the lamps were grouped in terms of the constituents that they contained. These sub-sets each contain a much wider range of lamp chromaticities than the "identical chromaticity" or "restricted chromaticity" sub-sets discussed previously, and significant rank order differences were found to be present in five sub-sets out of the nine. This seems to indicate that lamp chromaticity could be used as a very general guide to performance, in order to avoid including too wide a chromaticity range in groups of lamps that are being assessed for their suitability in television scene lighting, using Consistency Index predictions. The results described in the previous paragraph indicate that under these conditions reliable assessments of lamp rank order will be obtained.

3.3 The use of the reference camera analysis characteristics for calculating Television Consistency Index values

It was outlined in Sections 1 and 2 of this Report that, if an Index value calculated using one set of camera analysis characteristics could be used to predict the value that would be obtained using another such set of characteristics (within a reasonably small margin of uncertainty), then a "reference" set of camera analysis characteristics could be used in calculating a "general" Index value for a particular lamp, independently of any particular practical-camera characteristics. The set of reference camera analysis characteristics shown in Fig. 2 has been derived for the purpose of representing practical extended-red colour cameras without invoking the characteristics of particular practical cameras of this type. The question then arises whether or not this set of characteristics is the most suitable that could be derived for this purpose. Work carried out using linear regression analysis indicates that the reference characteristics of Fig. 2 are considerably "better than average" in predicting Index values, when the accuracy of prediction (measured by the average correlation coefficient) given by these and all eight extended-red practical sets of characteristics is considered. Nevertheless, two of the practical cameras showed (by a small margin) better accuracy of prediction using this measure of performance. In the rank order difference analysis involving the grouping of "hypothetical" lamp spectral power distribution into sub-sets of identical lamp phosphors or additives, on the other hand, it was found that fewer significant rank order differences were obtained when the extended-red reference analysis was one of the pair of camera characteristics involved in the comparison, as compared with the cases when any one of the practical cameras was involved. This method of analysis therefore showed the reference camera analysis characteristics as being the most suitable for representing practical cameras. Because of the differences found between one practical camera and another it is hard to envisage a further set of camera characteristics which would give a markedly better representation of all practical cameras than is the case with the present reference camera analysis. Indeed, the best that can really be expected from the reference camera analysis is that the disagreement between Index values calculated for a particular lamp with its use and those calculated using practical camera characteristics should on average be no greater than the corresponding average disagreement when two practical camera characteristics are involved. The present reference camera analysis appears to satisfy this criterion and it therefore seems appropriate to select it for representing all practical cameras. The fact that it was derived without invoking any practical camera means that there can be no tendency for it to convey any implications which might encourage the acceptance (or rejection) of a particular manufacturer's product: this might occur if a practical camera were to be used as a "reference".

3.4 A brief survey of "worst Index" results

This discussion relates to the worst (numerically lowest) Consistency Index value obtained over the complete test colour set, and to the particular test colour giving this Index value (see Items iii and iv of Section 2.1). A count has been made of the number of occasions on which any test colour gave rise to a "worst Index" value, using both of the lamp spectral power distribution sets described in Section 2.4. The extended-red camera analysis characteristics have again been used. Fig. 7 shows the overall result of this survey. Each point on the diagram has coordinates indicating the chromaticity of the test colour concerned, and the area of the circle round it is proportional to the percentage of worst Index results given by that test colour. It can be seen that although

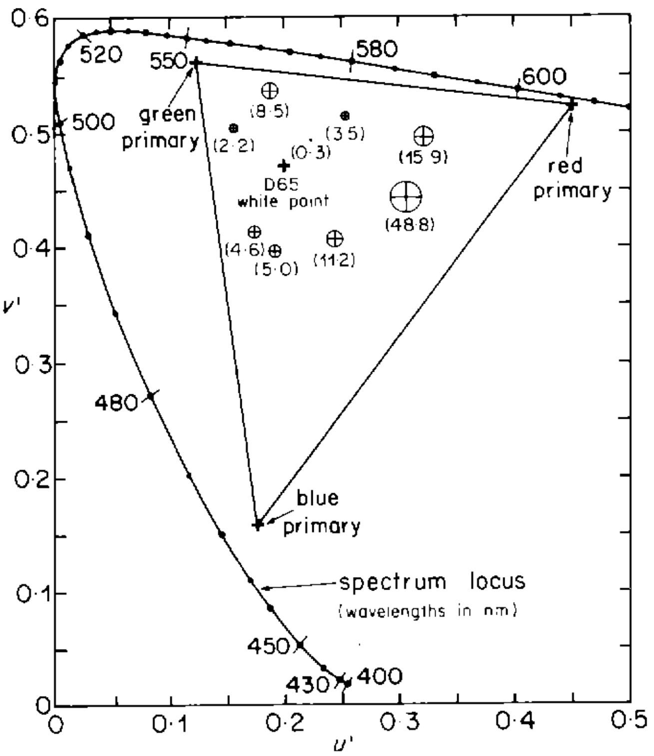

Fig. 7 - Chromaticities of test colours giving "worst Index" values.

Area of circle surrounding point proportional to percentage of worst Index values (also shown in brackets).

colours in the "pink" or "purple" regions of the chromaticity diagram predominate, there are a number of test colour chromaticities that give a significant fraction of worst Index results. For this reason the quotation of the test colour number in the complete expression of the Consistency Index appears to be justified. The reason for over half the "worst Index" values appearing in the "pink" and "purple" regions of the colour gamut is that, in general, the spectral power distribution of discharge lamps shows a deficiency in the far red, as compared with either of the reference illuminants. The effect of this on television colour reproduction is to cause such colours to shift towards blue. This reproduction error is particularly noticeable when using the P_{3000} reference illuminant, since the power differences between the reference and test illuminants in the far red are then greater than if the D_{65} reference is involved. In this case over 70% of the worst index values are given by the pink or purple test colours. It is of course true that an important benefit of using discharge lamps for scene lighting is the reduction of the relative power of the infra-red component: however the phenomenon of the worst-case errors appearing mainly in the pink and purple test colours seems to show that this power reduction starts at too short a wavelength. Control of the analysis characteristics of a colour television camera in the far red is an important problem in "present-day" cameras as the camera tube itself is inherently very sensitive at such wavelengths: indeed camera tubes often have an "infra-red" filter incorporated into their face-plates. The problem was much less severe when the earlier "narrow-red" camera tubes were used as these were insensitive to wavelengths above about 650nm (see Section 3.6).

3.5 Test colour sets

Regression analysis has been carried out between Index values using three test colour sets, as follows:-

1. The "original" test colour set of 25 test colours used in all the theoretical work up to the present time. (Note that this set includes eight skin tones.)

2. The "Macbeth" test colour set[11]. This consists of the measured spectral reflectance characteristics of the 18 colour samples used on a Macbeth Colour Checker, which correspond to numbers CR35 to CR52 inclusive in a proposed CIE set of test colours for colour reproduction. The first two colours represent Dark and Caucasian skin tones respectively and can be used to obtain a skin tone index. The remaining 16 colours were used to calculate the overall index.

3. A set of test colours, based on the "EBU" test colour set. This comprises the proposed CIE test colours CR01 to CR08 inclusive (the desaturated colours CIE TC-3.2 numbers 1 to 8) plus six colours of medium saturation considered for use by the European Broadcasting Union (EBU) corresponding to proposed CIE colours numbers CR21 to CR26 inclusive. This set of test colours does not contain any skin tones. (It may be noted that the test colour set as described above is in fact a subset of the full "EBU" set, which also contains the colours CIE 9-14 inclusive.)

Each set of calculations was carried out using the procedure described in Section 3.1, and using the television system parameters described in Section 2. When calculating Index values using the "new" test colour sets (Items 2 and 3 above), however, it was found that these sets contained samples having spectral reflectances which produced separation signals higher than those from the 60% reference white. A facility was therefore incorporated into the program used to calculate the Index values which emulated a camera with "auto-iris". The camera was considered to be

initially set-up on a 60% reflectance white and was then colour balanced. This provided a 100% video signal in each of the camera's separation channels. If a set of test colours contained samples which produced signals greater than given by the reference white, the levels of all the separation signals were reduced by the same factor to bring the level of the largest signal to the reference white level. In other cases, where no separation signal exceeded the reference white level, the original signal levels were not altered.

It is worth noting that the above-described procedure may be implemented in two ways. If, on the one hand, the two sets of separation-signal values corresponding to the use of either the test lamp or the reference illuminant are normalized independently of each other, then the general luminance levels of the two displayed pictures found in the two cases could well be different (in other words, if an achromatic test colour was introduced into the test colour set, giving colour separation signal levels below the largest value to which all the others were normalized, then the corresponding display luminance woud be different when using the test lamp and the reference illuminant). This factor would affect the calculated value of Television Consistency Index. On the other hand, signal normalization could be carried out by first calculating colour-separation signal levels for both the test lamp and the reference illuminant, and then selecting the largest colour-separation signal among all these values as the normalization factor. This procedure avoids the change in luminance level which could take place when the two sets of colour-separation signals are normalized separately, and is perhaps more rigorously correct from a purely "colorimetric" point of view. However, if different lamps are used in practice to illuminate scenes in a production which are then to be intercut for sequential viewing, the shooting of those scenes is likely to take place on separate occasions with appropriate adjustment of camera exposure in each case. The first procedure (separate signal normalization for each scene illuminant) is therefore more in accord with operational practice and has been adopted in the calculation of the Television Consistency Index. Changes in Index value which may arise because of the use of this procedure then reflect changes in overall picture reproduction that would occur in practice.

Only "overall" Television Consistency Index values (averages over a range of test colours representing the colour television reproduction gamut) were considered. Furthermore, only linear regression analysis of the Consistency Index values was used in the present work. The "non-linear" regression analysis technique, involving a comparison of the logarithms of the colour-difference corresponding to Consistency Index values (see Fig. 5) has not been used.

The results of the analysis described above showed that (as previously mentioned in Section 2.3) the degree of correlation between Index values obtained using each of the three test-colour sets (and the same camera analysis characteristics) was the same as the correlation obtained using different camera analysis characteristics (and using the same test-colour set). The absolute values or "scale" of the calculated Indices do however depend on the test colour set used and so it is necessary to specify a particular set when putting forward parameters for a "general" Index.

It was also found that the uncertainty in Television Consistency Index value, due to the use of one set of camera analysis characteristics rather than of another, is virtually independent of the test colour set used in the calculations. This latter consideration indicates that it is unlikely, at least on the evidence at present available, that a particular test colour set can be selected which is "best" in the sense of giving greater accuracy of Television Consistency Index prediction. These results also indicate that the extensive theoretical work carried out on this subject using the original test colour set is applicable when other test colour sets are involved (provided, of course, that such sets reasonably explore the colour television reproduction gamut).

The conclusions which were made from the analysis discussed above confirmed earlier work involving a large number of colours from which groups of colours were taken to form a number of test-colour sets. Results obtained using such sets of test colours do have to be interpreted with some care, since there will be a tendency for correlation to increase as greater numbers of colours are selected to make up the test colour sets (i.e. as the sets approach more closely the original distribution of colours). Nevertheless, this work showed that a meaningful "overall" Index could be calculated with fewer colours than the 25 originally used, if the distribution of colours was carefully considered.

It is important to note that the individual test colour patches on Macbeth Color Checker test charts, now currently available, although very similar in appearance to the patches on the originally-published chart, are not necessarily identical to them in terms of spectral reflectance characteristics: furthermore, the spectral reflectance characteristics of corresponding patches on individual charts may differ from one another. If this set of test colours is chosen as being suitable for use in calculating the "general" Television Consistency Index, then a defined set of spectral reflectance characteristics must be used in these calculations (see Appendix 1). Taken by itself this would seem to indicate that the Color Checker test colour set had little special merit over any other set of

hypothetical spectral data, apart from its particular property of covering the Television colour gamut. Nevertheless, Color Checker charts are widely used and provide a ready and familiar method of assessing the colour reproduction properties of a television system. Provided that the inconsistencies in the spectral reflectance characteristics of individual charts are not so great as to lead to serious errors in such an assessment, as the ready availability and wide acceptance of these charts by television organisations would seem to indicate, the use of the "defined" Color Checker data in calculating the General Television Consistency Index would have the merit of providing a worthwhile (if not strictly accurate) correspondence between theoretically-obtained Index values and practically-observed colorimetric performance. It may be noted that neither of the other two sets of test colours are as easily available in a practical realization. It is thought that the spectral reflectance characteristics of the two "skin tone" test colours on the Color Checker charts are sufficiently close to those of real skin for them to be used in the calculation of a skin tone Television Consistency Index (see Section 2.1), although work to test this assumption is as yet incomplete.

3.6 The use of "narrow-red" colour television cameras

The work so far discussed refers to the use of "extended-red" colour cameras in which the long-wavelength red response is not restricted (to below about 650 nm) by the characteristics of some lead-oxide camera tubes. Cameras are however still in use (and indeed provide certain advantages in fields other than camera colorimetry) in which this restriction applies. Analysis of "overall" Consistency Index data using this category of camera characteristics was rather restricted since only three sets of practical camera analysis characteristics were available, although historically this work preceded the work using the extended-red category of cameras. The results of linear regression analysis using narrow-red camera characteristics showed that the degree of correlation between Index values obtained using one such set of characteristics and another, although still high, was lower than when extended-red characteristics were involved. The uncertainty in individual Index values was ± 13 (compared with ± 7 for the case of extended-red cameras: see Equation 3). Similar analysis involving narrow-red cameras on the one hand, and extended-red cameras on the other hand, gave (not unexpectedly) a still lower degree of correlation and led to an uncertainty value of ± 16. Non-linear regression analysis was not attempted in either of these cases, but this method of analysis would still be valid and would lead to a reduction of uncertainty for high Consistency Index values as outlined in Equations 3 and 4. Nevertheless it can be seen that the Consistency Index values give a rather broad indication of the suitability of lamps for television lighting when the narrow-red category of colour television camera is concerned. Expressed another way, on the evidence of the three practical narrow-red cameras used in the analysis, such cameras differ between themselves more markedly than is the case with extended-red cameras, when the effect of changing the source of scene illumination from one lamp to another is concerned. In these circumstances no method of lamp categorisation can give a meaningful distinction between the general behaviour of two lamps of roughly similar colorimetric performance. The same argument applies when considering colour television cameras in general (i.e. ignoring the distinction between the narrow-red and extended-red categories).

4. PRACTICAL FIELD TRIALS OF THE TELEVISION CONSISTENCY INDEX

4.1 Practical details

In deriving the Television Consistency Index for a lamp, the calculated colorimetric performance of a television channel, using the lamp under test as scene illumination, is compared with the performance of the same channel using a "reference" illuminant. The comparison is made using a colour difference formula to quantify differences in the reproduction of each of a number of test colours, the test colour set reasonably exploring the gamut of television reproduction. The same concept is used in carrying out the practical field trials[9]. A television scene is illuminated first with the lamp under test and then with the reference illuminant, and each is recorded: subsequently the recording is edited so that observers may compare the reproduction of the scene obtained using the two lamps, and their opinion as to the consistency of colorimetric reproduction is noted using a suitable subjective scale.

In order to make the results of tests carried out at different times and by different organizations directly comparable, the conditions of recording the test material and conducting the subjective tests were standardized. The scenes involving the use of different lamps were recorded in one continuous session so that camera line-up conditions would change as little as possible between each scene, and recordings of test charts were included (but not shown to the observers) to enable corrections to be made to the video signal if necessary. However, the scene itself differed from one set of tests to another, in an attempt to include a variety of "typical" television picture material. The voltage applied to each lamp was accurately measured and an adequate warm-up time was allowed before

making the recording. The test and reference signals were either presented to the observer alternately, to represent the effect of "inter-cutting" between scenes involving different lamps, or in some cases presented as a composite "split-screen" picture so that corresponding areas of the two pictures could be directly compared. Observers were asked to return one of the five opinions shown in Table 1: the "grades" associated with each opinion enabled the results to be handled numerically.

Table 1
Subjective grades

Opinion	Grade
Pictures show excellent consistency	5
Pictures show good consistency	4
Pictures show moderate consistency	3
Pictures show poor consistency	2
Pictures show very poor consistency	1

Three sets of comparisons have been carried out, using eight test lamps (three fluorescent and five high-intensity discharge). The number of lamps used was a compromise between obtaining test results over as large a sample as possible on the one hand, while keeping the number of test assessments within reasonable limits, to prevent observer fatigue and to make gathering the test material practicable, on the other hand. The correlated colour temperatures of the lamps were loosely grouped round two values, representing very approximately "daylight" and "studio" conditions. The lamps showed a wide spread between very good and rather poor colorimetric performance, although some grouping of both the Television Consistency Index and the General Colour Rendering Index values inevitably occurred. During the recording of the test material attention was paid to the technique of scene lighting so that the "modelling" (appearance of shadows etc.) changed as little as possible when one lamp was substituted for another: such differences could not however be entirely eliminated and represented a factor additional to the reproduced colorimetry which changed from lamp to lamp. Observers were advised to disregard such differences as far as possible, if they felt that they could with certainty distinguish between a change in modelling and a colorimetric change.

Two sets of comparisons were made using the studio (P_{3000}) reference illuminant. In the first of these comparisons the test scene consisted of two people (male and female) seated in front of a "pop-art" backdrop of a girl's face in bizarre colours, while for the second of the comparisons an Edwardian drawing-room scene was used, with a seated female figure in a dark dress reading a book. Both of these scenes used sets which had been adapted from previously-transmitted television productions, and they could therefore be regarded as "typical" programme material. The two tests were carried out by different broadcasting organizations. At a later stage, the recorded material used for the first set of tests was re-arranged so that one of the test lamps (Lamp No. 5) became the reference, as a substitute for using natural daylight for this purpose. Although this procedure could not give a precise correspondence between theoretical "daylight" indices and practical tests, statistical tests showed that Indices calculated using either daylight (D_{65}) or Lamp 5 showed very high correlation. Thus three sets of trials have been carried out so far:

Trial 1 – P_{3000} reference (37 observers)
Trial 2 – P_{3000} reference (27 observers)
Trial 3 – "Lamp 5" (daylight simulator) reference (18 observers): same test picture as Trial 1.

Details of the subjective test results obtained from these trials are shown in Appendix 2, while the calculated Television Consistency Indices for the lamps used in the tests are shown in columns 2, 3 and 4 of Table 2.

Table 2
Indices obtained for lamps used in practical field trials

Lamp	Television Consistency Index for indicated reference illuminant			General Colour Rendering Index
	P_{3000}	D_{65}	Lamp 5	
1	44.5	51.7	54.8	57.1
2	51.6	53.2	57.7	57.4
3	30.7	24.1	30.1	30.6
4	80.8	82.9	87.6	89.6
5	81.4 76.0	92.8	100	97.3 94.4
6	72.1	51.0	57.6	77.5
7	69.0	71.6	75.9	76.3
8	77.0	72.6	79.0	78.7
9 (P_{3000})	100	75.3	81.4	100
D_{65}	75.3	100	92.8	100

Where two values are shown for Lamp 5, the left-hand one refers to Trial 1 and the right-hand one to Trial 2.

The right-hand column of Table 2 shows corresponding values of the General Colour Rendering Index. Comparisons between the practical and calculated estimates of lamp performance are discussed in the following Sections of this Report. It should be noted that the Television Consistency Index values shown in Table 2 have been calculated using a test colour set

consisting of the fourteen test colours specified in CIE Publication 13.2[3] together with one additional Caucasian flesh colour. However, the correlation between the values obtained using this "fifteen test colour" set and corresponding values obtained using the "25 test colour" set employed for the theoretical work (see Section 3.5) is very high.

4.2 Results

4.2.1 Tests using studio (P_{3000}) reference illuminant

The results of the first two sets of trials referred to in Section 4.1, in which a tungsten lamp was used as reference, are compared with corresponding Television Consistency Index values involving the P_{3000} reference illuminant in Figs. 8, 9 and 10, and in the first three lines of Table 3. Figs. 8 and 9 refer respectively to the mean subjective grades (see Table 1) obtained using the "alternate presentation" and "split-screen presentation" viewing conditions used in the first series of tests, while Fig. 10 shows the same relationships in the case of the second series of tests in which only alternate presentation of test and reference conditions was used. It should be noted that a "control" condition was incorporated in the second series of tests (but not the first) in which the reference (tungsten) lamp was compared with itself: this is referred to as "Lamp 9" in Fig. 10. Results obtained using this lamp were included in the calculations. Comparing Figs. 8 and 9, which it must be remembered relate different presentations of the same test material, it can be seen that a much higher degree of correlation was obtained when the split-screen method of presentation was used. In fact, statistical tests show that the degree of correlation in the case of the "alternate presentation" results is not significant at the 5% level. The correlation in the case of the "split-screen" results from the first series of tests, and the correlation found for the second series of tests (alternate presentation: see Fig. 10) is however significant at this level. In the latter case this degree of correlation is found despite the apparently anomalous behaviour of Lamp 5 which is rated poorer in terms of consistency of colour reproduction than its Television Consistency Index value would indicate. In fact Lamp 5 failed shortly (in terms of burning time) after use in making the test material and it is possible (although not certain) that its spectral power distribution was anomalous on this occasion.

Reasons for the occurrence of particular subjective test results are often hard to determine, and the present subject-matter is no exception. The difference between the results shown in Figs. 8 and 9 evidently relates to the greater ease with which colorimetric comparisons may be made when the coloured areas being compared are presented simultaneously, as compared to the case when memory (however short-term) is involved. Furthermore, the differences between the test and reference conditions

Table 3
Correlation between calculated Index value and practical subjective grade

Subjective grade parameters			Index parameters			
Reference lamp	Trial No.	Picture presentation (note 1)	Type	Reference illuminant	Correlation coefficient	Scatter diagram Fig. No.
Tungsten	1	A	R_t	P_{3000}	0.656	8
Tungsten	1	S	R_t	P_{3000}	0.940	9
Tungsten	2	A	R_t	P_{3000}	0.870	10
Lamp 5	3	A	R_t	Lamp 5	0.870	11
Lamp 5	3	S	R_t	Lamp 5	0.683	12
Tungsten	1	A	R_a	(Note 2)	0.721	13
Tungsten	1	S	R_a	(Note 2)	0.946	14
Tungsten	2	A	R_a	(Note 2)	0.804	15
Lamp 5	3	A	R_a	(Note 2)	0.642	16
Lamp 5	3	S	R_a	(Note 2)	0.375	17

Note 1. A = Alternate presentation.
S = Split-screen presentation.

Note 2. Reference illuminant as determined by correlated colour temperatures of individual lamps.

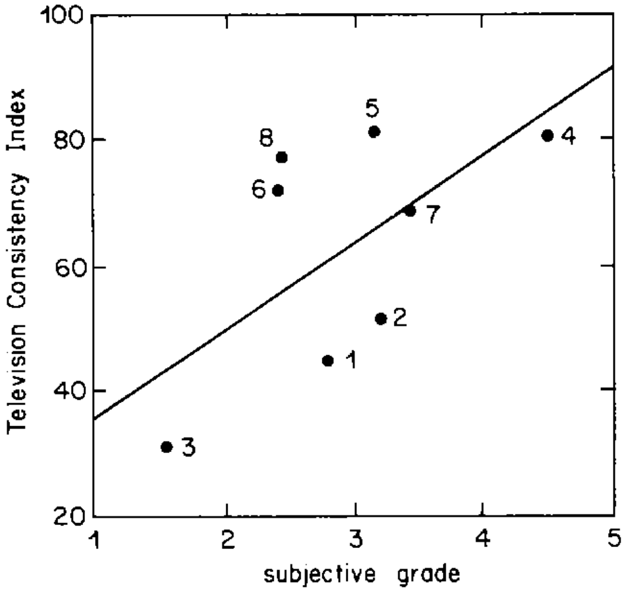

Fig. 8 - Comparison between practical subjective grade and Television Consistency Index: Trial 1, alternate presentation, P_{3000} reference.
Correlation coefficient ... 0.656

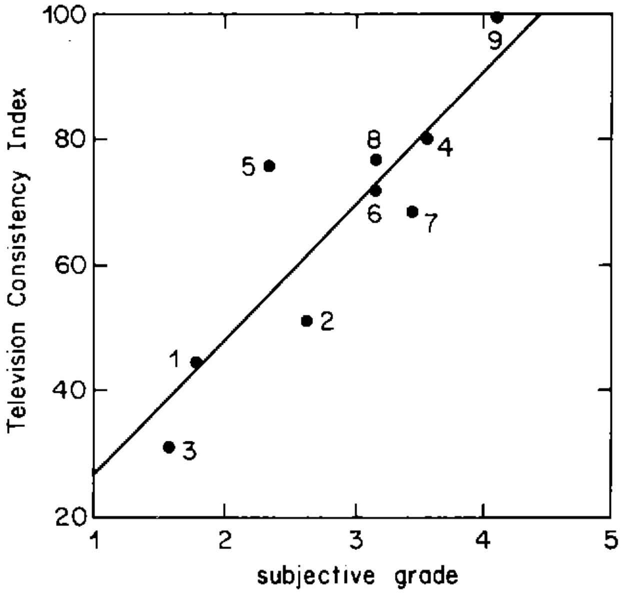

Fig. 10 - Comparison between practical subjective grade and Television Consistency Index: Trial 2, alternate presentation, P_{3000} reference.
Correlation coefficient ... 0.870

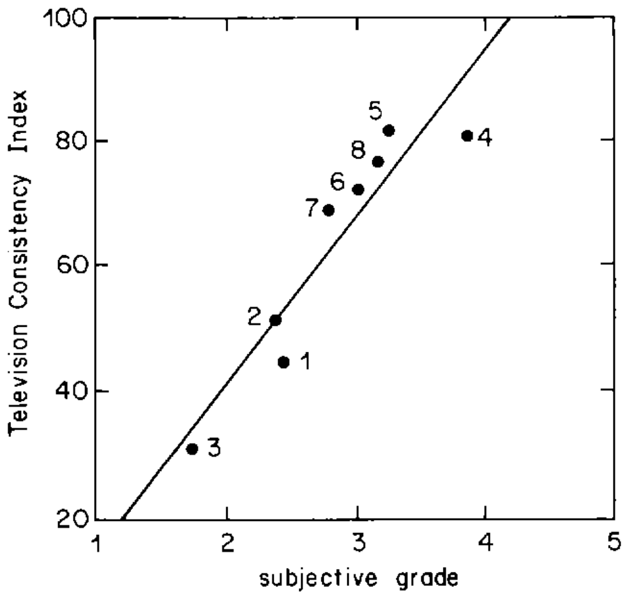

Fig. 9 - Comparison between practical subjective grade and Television Consistency Index: Trial 1, split-screen presentation, P_{3000} reference.
Correlation coefficient ... 0.940

caused by changes in shadow detail were less evident in the case of the split-screen comparisons. The differences between Figs. 8 and 10 are harder to explain as "alternate" viewing was involved in both cases. It might have been expected for results from the second series of tests to have shown a greater scatter than those from the first series, as the scene used for the second series was considerably more "three-dimensional" than was the case for the first series, and "lamp-to-lamp" differences in shadow detail were correspondingly greater. The fact that the converse was actually the case may be due to the category of observer used in the two series of tests: assessments were made predominantly by technical staff in the second series, accustomed to making judgments of television colour reproduction as part of their work, while the observers in the first series contained a large proportion of people whose work involved artistic judgments of colour (scene designers, wardrobe and make-up assistants etc.) but who were not involved as part of their work in comparisons between two differing reproductions of the same scene. Considerations of this sort raise the question of the general validity of specialist subjective test results vis-a-vis the opinions that the general public would hold when presented with the same test conditions. It is usually thought that specialist opinion provides the better basis for operational decisions (in the present case the use of one lamp rather than another for scene lighting) but that account has to be taken of opinions (when available) when the result of this decision is presented to the numerically far greater number of observers that the general public represents. Only then can the inevitably larger "scatter" in individual opinions be accommodated in statistical terms.

Attempts have been made, using multiple regression analysis, to combine values of the overall, worst and skin-tone Indices into one overall number which shows a higher degree of correlation with the subjective test results than do any of the individual Index values. It has been possible to achieve this result in each of the test conditions represented by Figs. 8, 9 and 10. In the case of the Fig. 8 conditions ("alternate" viewing, first series of tests), however, the relationships used to combine the individual Index values into one number are very "ill-conditioned",

particularly in the appearance of a large constant term which is hard to explain on theoretical grounds. Furthermore, the weighting coefficients (and constant term) assigned to the various individual parameters differ from test condition to test condition and at present there is not enough evidence to suggest a set of such coefficients which could be recommended as a general formulation of a "single-number" Index. This method of approach is however very powerful in statistical terms and could be of use if enough practical data could be collected to support it.

In terms of rank order, most of the rankings obtained using practical grade values did not differ significantly from the rankings obtained using Television Consistency Index values, using the method of analysis outlined in Section 3.2. However, the rank order obtained using "alternate" presentation in the first series of tests did not satisfy this criterion: this is in agreement with the result obtained using regression analysis (see Fig. 8).

4.2.2 Tests using Lamp 5 as reference illuminant

Figs. 11 and 12, which refer respectively to the "alternate presentation" and "split-screen presentation" viewing conditions, show the results of the third set of trials (see Section 4.1) in which Lamp 5 was used as reference in both the practical tests and in the Television Consistency Index calculations (see also lines 4 and 5 of Table 3). In these Figures "Lamp 9" is the original tungsten reference lamp as used in the first two sets of trials. Lamp 5 was also compared with itself, the corresponding Index value being 100: these results were included in the calculations. The practical subjective grades are mean values over 18 individual results. The correlation between practical grade and calculated Index value is better than was the case in the first set of trials using the P_{3000} reference under the "alternate presentation" viewing conditions (compare Figs. 8 and 11, and Figs. 9 and 12). In fact, the split-screen presentation gave a considerably lower correlation than the alternate presentation when Lamp 5 was used as reference. It is hard to reconcile this finding with the assumption that the comparison between test and reference pictures is made easier when the split-screen style of presentation is used (see Section 4.2.1). It may however be noted that for both types of viewing conditions, the mean subjective grade for the same (Lamp 5/Tungsten lamp) comparison was considerably less favourable (numerically lower) when Lamp 5 was used as a reference (2.4 for alternate viewing and 1.9 for split-screen viewing), compared with the case when the tungsten lamp was the reference (3.1 and 3.2 for alternate and split-screen presentations respectively). A possible explanation lies in the fact that during the tests the reference picture is presented, overall, for about half the total duration of the tests (excluding the interval between one test and another, when no picture is presented). Thus during the tests the "overall" colour reproduction is biassed towards that of the reference illuminant, and individual pictures from the different test lamps tend to be observed in relation to this overall condition. To a greater or lesser extent, all the test discharge lamps gave rise to errors in colour reproduction due to the lack of far-red radiation, as described in Section 3.4, while the

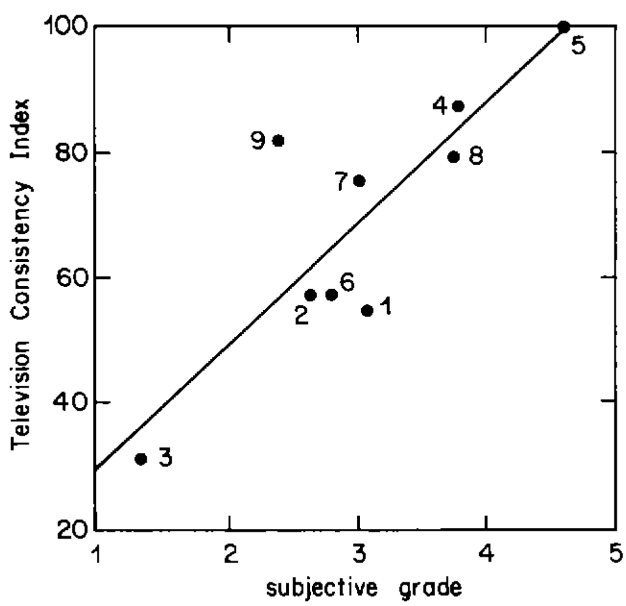

Fig. 11 - Comparison between practical subjective grade and Television Consistency Index: Trial 3, alternate presentation, Lamp 5 reference.
Correlation coefficient ... 0.870

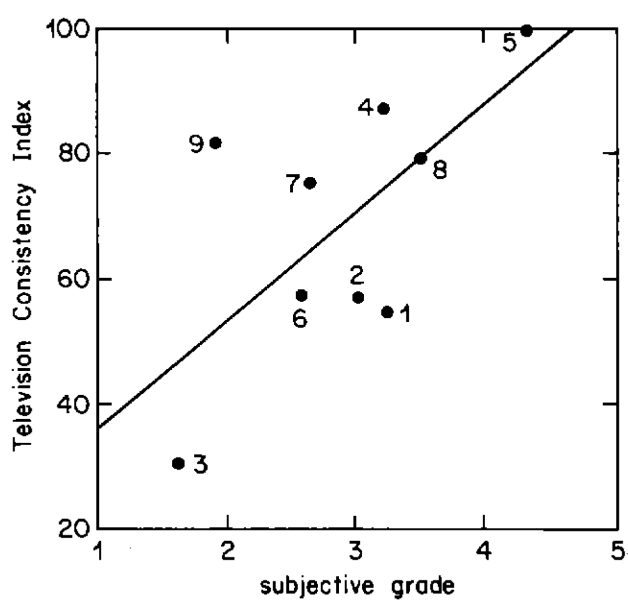

Fig. 12 - Comparison between practical subjective grade and Television Consistency Index: Trial 3, split-screen presentation, Lamp 5 reference.
Correlation coefficient ... 0.683

tungsten lamp did not show this effect. When the tungsten lamp was used as a reference, pictures from all the "test" lamps differed from that obtained from the reference lamp in the same general manner, although to a different degree. When Lamp 5 was used as reference, however, the picture obtained using the tungsten lamp as one of the "test" lamps appeared notably "different" to all the others (including the reference picture) and therefore attracted a poorer grading in terms of consistency of colour reproduction. This effect was more marked in the case of the "split-screen" viewing conditions, and the "down-grading" of the tungsten lamp was correspondingly more pronounced, than in the situation when alternate presentation was used. A genuine D_{65} reference would not necessarily show this tendency to the same extent, since there is significant radiated power at wavelengths up to at least 800 nm, above which the camera response should be zero.

4.3 The use of the General Colour Rendering Index

In view of the "scatter" of results obtained in the Field Trials, the question arises as to whether a reasonable correlation between practical result and Index value would have been obtained if the General Colour Rendering Index (R_a)[3] (see Fig. 1) had been used rather than the Television Consistency Index, bearing in mind the close relationship that clearly exists between them. Figs. 13, 14 and 15 show such comparisons, referring respectively to the "alternate presentation" and "split-screen presentation" results from the first series of tests, and the (alternate presentation) results from the second series of tests, while Figs. 16 and 17 similarly show results obtained in the third series of tests using the "Lamp 5" reference. (See also the last five lines of Table 3). Comparisons of Figs. 8 and 13, and Figs. 9 and 14, indicates that in the first series of tests a slightly better fit between mean subjective grade and Index value is obtained using the Colour Rendering Index under both alternate presentation and split screen viewing conditions. On the other hand, Figs. 10 and 15 show for the second series of tests (using alternate presentation) a small advantage in using the Television Consistency Index. In the third series of tests, using the Lamp 5 reference illuminant, comparing Figs. 11 and 16 and Figs. 12 and 17 show a fairly strong advantage in using the Television Consistency Index in both alternate and split-screen viewing conditions, although in all cases considerable scatter in the comparisons obtained for individual lamps was evident.

Overall, the evidence as to whether or not the extra complication of providing an Index referring specifically to television scene lighting is worthwhile is conflicting: some results indicate a rather slight advantage in using the Colour Rendering Index while others show a distinct preference for the Television Consistency Index, but with generally lower levels of correlation. The subject is discussed further in Section 5.

As far as rank orders are concerned, the ranking obtained using the Colour Rendering Index is also just as valid as that involving the Television Consistency Index in representing the ranking obtained from the practical tests.

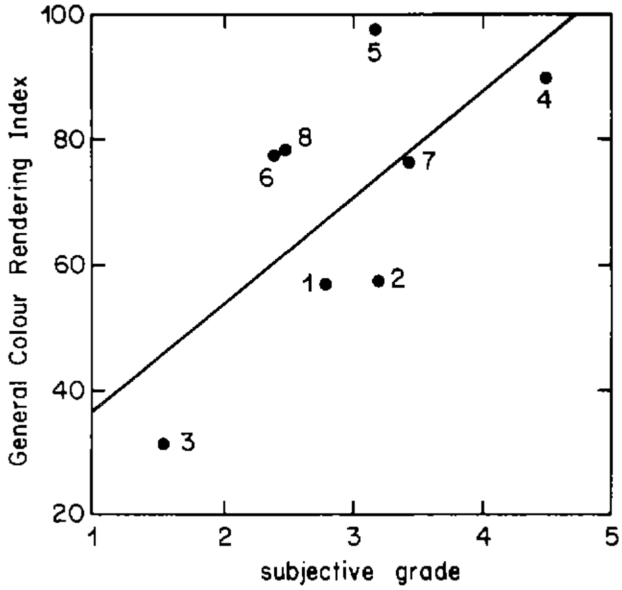

Fig. 13 - Comparison between practical subjective grade and General Colour Rendering Index: Trial 1, alternate presentation, P_{3000} reference.
Correlation coefficient ... 0.721

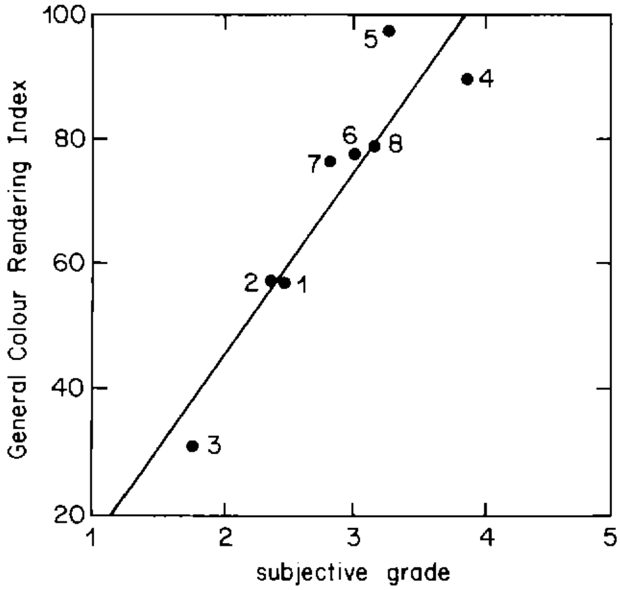

Fig. 14 - Comparison between practical subjective grade and General Colour Rendering Index: Trial 1, split-screen presentation, P_{3000} reference.
Correlation coefficient ... 0.946

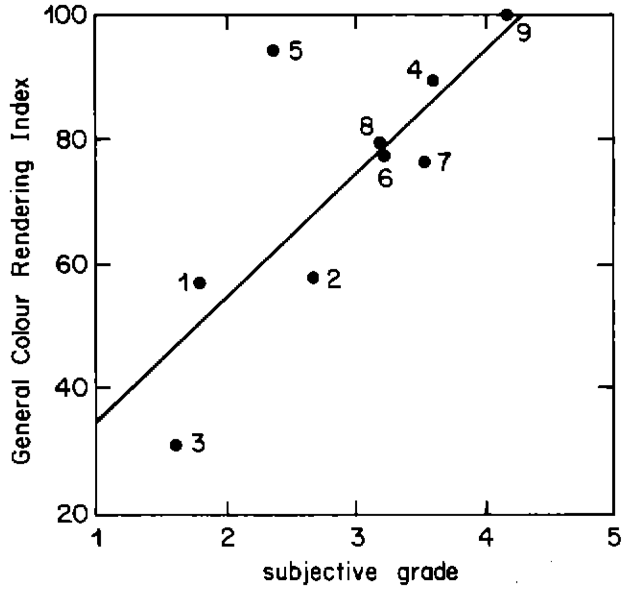

Fig. 15 - Comparison between practical subjective grade and General Colour Rendering Index: Trial 2, alternate presentation, P_{3000} reference.
Correlation coefficient ... 0.804

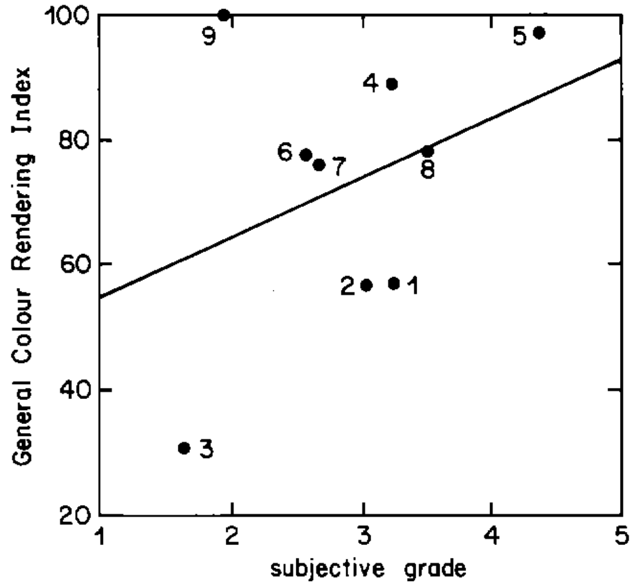

Fig. 17 - Comparison between practical subjective grade and General Colour Rendering Index: Trial 3, split-screen presentation, Lamp 5 reference.
Correlation coefficient ... 0.375

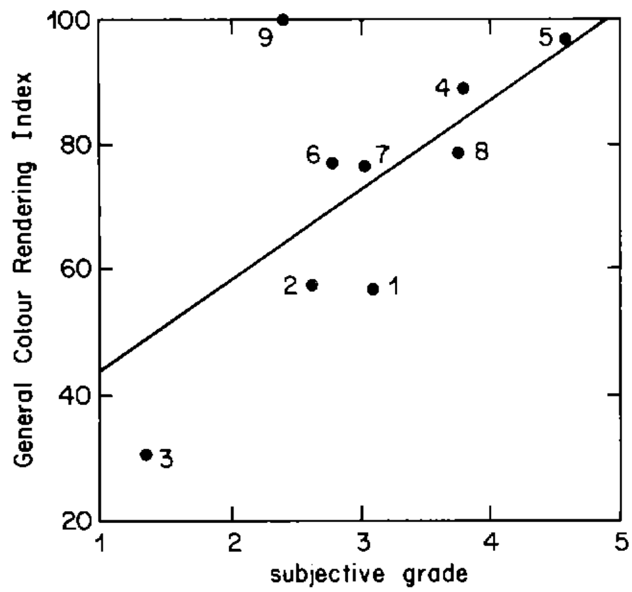

Fig. 16 - Comparison between practical subjective grade and General Colour Rendering Index: Trial 3, alternate presentation, Lamp 5 reference.
Correlation coefficient ... 0.642

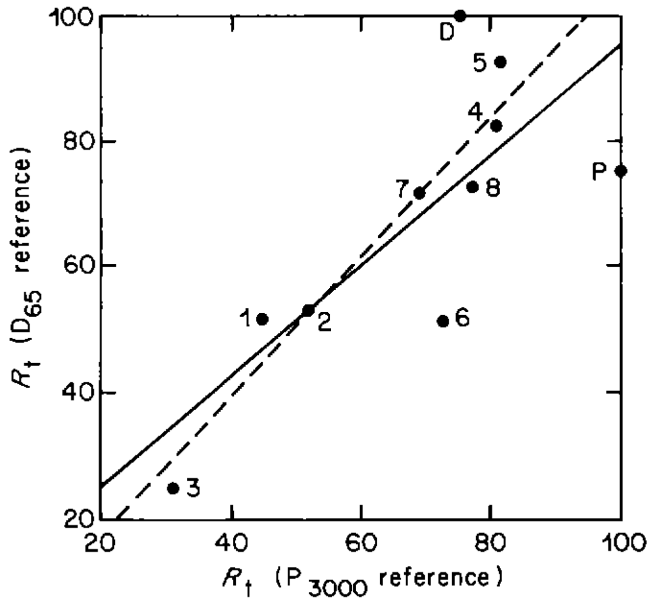

Fig. 18 - Comparison between Television Consistency Indices using P_{3000} and D_{65} references.

——— Regression line for all lamps
Correlation coefficient ... 0.776

– – – – Regression line excluding lamps D, P and 6 (see text)
Correlation coefficient ... 0.968

5. DISCUSSION

The field trials have shown that there is very strong correlation between the Television Consistency Index value found for a particular lamp and a given reference illuminant on the one hand, and the subjective assessment of consistency on the other. Taken by itself, this confirms that the Consistency Index method of categorizing lamps in respect of their suitability for television scene lighting is valid, bearing in mind the particular conditions and the uncertainty limits within which the Index is meant to be used. The field trials have also shown that the Colour Rendering Index value gives high correlation with the practical assessments. Although the correlation is not so strong as is found for the Television Consistency Index, the trials do not give a clear-cut answer, in purely statistical terms, to the question as to whether the use of the Television Consistency Index does or does not have a distinct advantage over the Colour Rendering

Index as a method of lamp categorization for television scene lighting. This difficulty appears to be due both to the relatively small number of lamps used in the field trials (nine, including the tungsten "reference": this may be compared with the total of 129 used in the theoretical work), and to the "non-normal" statistical distributions of consistency index and subjective grade values which are inevitable in a small sample. This latter point may be illustrated by comparing the ten Television Consistency Index values obtained using a P_{3000} reference illuminant with those found using the D_{65} reference (Fig. 18). In this figure the points numbered 1 - 8 refer to the "practical" lamps, and the points P and D refer respectively to the two reference illuminants treated as practical lamps. In each of these two latter cases the index value is 100 when the "lamp" is compared with itself as reference, and a lower value when it is compared with the other. Over all the ten comparisons the correlation coefficient is 0.78, a fact which is perhaps not surprising in itself as a high degree of correlation would not be expected between the two sets of Index values. However, if the two references (P and D) are excluded, the correlation coefficient over the remaining eight comparisons becomes 0.89: furthermore, if Lamp 6 (which can be seen from Fig. 18 not to follow the general trend) is also excluded, the correlation coefficient over the remaining seven comparisons rises further to 0.97. It may be noted that in terms of probabilities of correlation coefficient values arising purely by chance, the values of 0.78, 0.89 and 0.97 correspond to probabilities of 0.74%, 0.3% and 0.03% respectively. Thus the statistical "behaviour" of this assembly of Index value comparisons is largely governed by the behaviour of only three of its members, or in other words the set of lamps involved in these comparisons is not suitable for making detailed comments on the subject-matter of the comparisons (i.e. the differential behaviour of Index values using one or other reference illuminant). A similar argument may be developed concerning the comparisons between the use of the Television Consistency Index and the General Colour Rendering Index. Tests (or at least practical experience) using a much larger number of lamps are required before the relative merit of the use of the Television Consistency Index, as opposed to the use of the General Colour Rendering Index, can be ascertained with reasonable certainty. The results of the present series of tests seem to indicate, however, that although for many lamps the two methods of deriving Index values are probably of roughly equal merit, in the case of some lamps the Television Consistency Index does indicate a real difference in the consistency of colour reproduction when comparisons are made using either one reference illuminant or the other. In these cases the Television Consistency Index is superior to the General Colour Rendering Index in describing lamp performance. Unless it can be shown that the proportion of lamps which behave in this latter manner is so small as to be insignificant, it may be concluded that the Television Consistency Index method of lamp categorization provides useful information on the behaviour of lamps as television light sources, which is not available from the corresponding General Colour Rendering Index value.

It is worth noting that treating the reference illuminant as a practical source, as in the foregoing discussion, is a valid procedure as it represents a frequently-occurring operational situation. One example of this is in the televising of sports events which start in daylight and end under floodlights: an edited version of the events would contain the "intercutting" between pictures obtained using the two sources which corresponds to this Index value. Another example is in the use of "colour temperature raising" or "colour temperature lowering" filters to re-balance a camera from studio to daylight illumination or vice versa with little adjustment to the colour separation channel gains. Adopting this technique, for instance, pictures from a camera initially balanced in studio illumination and then re-balanced using a colour temperature lowering filter for use in daylight could be intercut with pictures from another camera viewing the same daylight scene but electronically balanced for this illumination. From the colorimetric point of view the first camera is still balanced in studio illumination and intercutting between the two cameras therefore again represents the use of two sources which correspond to the Television Consistency Index value obtained when one reference illuminant is compared with the other. A corollary to this aspect of Index value calculation is that intercutting of pictures taken under studio and daylight conditions is generally regarded as satisfactory (in other words, the consistency of colour reproduction in the two cases is regarded as reasonable). The "overall" Index value for this scene illuminant change is 75 (to the nearest whole number) and this gives one indication of the magnitude of values that might be regarded as indicating acceptable consistency of colour reproduction. On the other hand, inspection of Figs. 8-12 shows on average that a degree of consistency rated as "good" (grade 4) corresponds to an Index value of 88. It would again seem (as in the case of the choice between the use of the Television Consistency Index or the General Colour Rendering Index, discussed above) that experience in the behaviour of the Television Consistency Index must be gained before the relation between Index value and the practical degree of consistency of colour reproduction can be evaluated.

It must not be forgotten that one of the purposes envisaged for the Television Consistency Index is to replace "correlated colour temperature" as a measure of lamp performance (see Section 1): the

Index is to be calculated using each of the reference illuminants in turn, and the reference illuminant giving the higher value will indicate whether the lamp is "studio compatible for television" or "daylight compatible for television" (see Section 2.2). If the idea of the Television Consistency Index was to be dropped and use made of the Colour Rendering Index instead, this facility would be lost, as only one Colour Rendering Index is calculated for any lamp. Indeed, the situation is even more anomalous than the provision of just one Index value indicates, because the reference illuminant used in calculating the Colour Rendering Index is selected with regard to the correlated colour temperature of the lamp in question: thus the use of the Colour Rendering Index instead of the Television Consistency Index involves the very quantity that the use of the Television Consistency Index seeks to avoid. As a compromise it could perhaps be suggested that a version of the Colour Rendering Index should be used, but calculated using the P_{3000} and D_{65} reference illuminants: however if this were to be done, extra Index values would still be involved and a re-calculation in this way could just as well be made using the full Television Consistency Index formulation. It may be noted that a dual index has already been proposed by other workers[8].

The lack of any practical tests involving the daylight reference illuminant is a regrettable shortcoming of the present work, although an attempt has been made to rectify this by using Lamp 5 as reference. It is unfortunately true that practical tests of the Television Consistency Index involve considerable expense both in the time taken to carry them out and in the sophisticated studio equipment which is required to obtain the test material. It must be remembered that the colorimetric shifts involved are sometimes quite small and easily masked by larger changes caused by poor technical facilities or operating techniques. It will in the long run probably be necessary to rely on building up a body of experience in the use of the Television Consistency Index and assess at a later date the usefulness (or otherwise) of the Index.

In discussing the correlation between practical subjective grade and theoretically-derived Consistency Index values, it must be borne in mind that both these quantities are subject to limits of uncertainty. The limits for subjective grade are twice the mean of the standard errors associated with the grades returned for each lamp, while those for Index value are obtained using Equation 3, Section 3.1. These limits show the scatter in the results in terms of the known uncertainties in both subjective grade (resulting from the varying opinions of different observers) and the overall Index values (resulting from the use of different colour cameras as described in Section 3.1). Fig. 19 for example, shows these uncertainty limits applied to the second set of field trials. The full line in Figure 19 is drawn to pass within the uncertainty limits of as large a number of points as possible, on the grounds that having determined the existence of such uncertainties in statistical terms it is unreasonable to expect any closer agreement between theory and practice. It can be seen that the majority of lamps are included: the anomalous behaviour of Lamp 5 has been discussed previously (Section 4.2.1). It may however be remarked that the use of different camera analysis characteristics has very little influence on the values of correlation coefficient obtained in the foregoing analysis.

In putting forward any argument in favour of using the Colour Rendering Index rather than the Television Consistency Index as an adequate description of lamp performance in respect of its suitability as a source of television scene lighting, it must be acknowledged that the uncertainty limits derived for the Television Consistency Index have to be transferred to the Colour Rendering Index values. The Colour Rendering Index itself does not carry any such limits since it is based on one set of colour analysis characteristics only (the "standard observer"). This in itself would appear to justify the work carried out in investigating the Television Consistency Index: even if the Colour Rendering Index was to be adopted as a means of categorizing lamps for television, the uncertainty limits due to the use of different cameras would still be relevant.

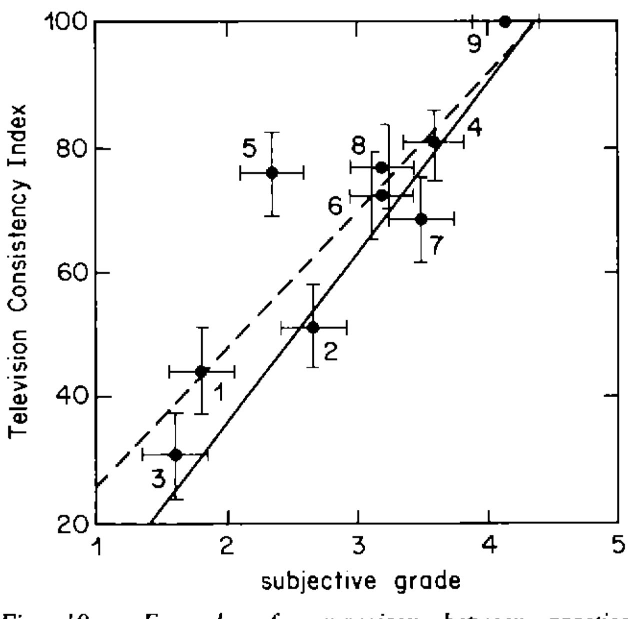

Fig. 19 - Example of comparison between practical subjective grade and Television Consistency Index, showing uncertainty limit lines (Trial 2, alternate presentation, P_{3000} reference: see Fig. 10).

——— Line drawn to pass within uncertainty limits for maximum number of points.
– – – – Regression line.

6. CONCLUSIONS

The programme of work described in this Report has led to the following achievements and results:-

(1) A "working model" of a colour television system, in the form of a computer program, has been developed.

(2) A method has been devised for evaluating the colorimetric effect of changing the lamp used for illuminating the scene being reproduced, as far as possible without including the imperfections of the reproducing process in this evaluation.

(3) Theoretical work has been carried out on a large number of average Consistency Index values, taken over a range of test colours representing the colour television reproduction gamut. This work has shown that, particularly in the case of the "extended-red" category of colour television camera, the Index is capable of providing a meaningful categorization of lamp performance which is not dependent on particular camera analysis characteristics. The differences which do in fact occur between one camera and another may be allowed for by assuming an "uncertainty" in Index value, such that two lamps having a difference of Index value within the prescribed limit are regarded as having the same performance, as far as their suitability as light sources for television scene lighting is concerned (see Equation 4). The same argument applies to the "narrow-red" category of colour television camera, except that the Index uncertainty is greater in this case.

(4) The theoretical work referred to in Paragraph (3) above has also shown that the degree of correlation between Index values obtained using different test colour sets (each of which covered the gamut of television colour reproduction) was, coincidentally, the same as the correlation obtained when using different camera analysis characteristics. The absolute value or "scale" of a Television Consistency Index value does however depend on the test colour set used, and so it is necessary to specify a particular set when putting forward parameters for a "general" Index. It was also found that the uncertainty in Television Consistency Index value, due to the use of one set of camera analysis characteristics rather than another, is virtually independant of the test colour set being used.

(5) The categorization of lamp performance independently of particular camera analysis characteristics, mentioned in paragraph 3 above, may be obtained by using a "reference" analysis in the calculation of Consistency Index values. Such an analysis has been devised without invoking any particular practical camera characteristics (see Fig. 2 and Equation 2).

(6) The Consistency Index method may be used to assess the likely performance of lamps in conjunction with any set of practical camera analysis characteristics, simply by using these characteristics to calculate "particular" Index values referring specifically to the camera in question.

(7) Consistency Index values may be used to determine the rank order of a number of lamps, in terms of their suitability as light sources for television scene lighting. The accuracy of prediction of such a rank order (particularly, again, in the case of the "extended-red" category of cameras), using the reference set of camera analysis characteristics, is often greater than would be expected from the Index uncertainty value discussed in Paragraph 3 above. Expressed another way, differences in lamp performance are often similar from one camera to another, even though "absolute" performance may differ between cameras. This relationship is particularly true if lamps of similar chromaticity (although having markedly different spectral power distributions) are being compared.

(8) Experience in the behaviour of the Television Consistency Index must be gained before the relation between Index value and the practical degree of consistency of colour reproduction can be evaluated. When, in due course, the appropriate limiting Index value which corresponds to satisfactory lamp performance in this respect has been determined, the Television Consistency Index may be used to categorize a lamp either as "studio compatible for television" or as "daylight compatible for television". To achieve this, Index values are calculated using

each reference illuminant in turn: the reference illuminant giving an Index value higher than the limiting value then indicates which of these two categories is appropriate. If neither Index values attains or exceeds this limit, the lamp may be deemed incompatible with both studio lighting and daylight. It may be noted that this assessment is intended to replace the use of correlated colour temperature as a description of lamp colorimetric performance in television scene lighting applications.

(9) Work carried out using the P_{3000} reference illuminant indicates that the General Colour Rendering Index gives almost as good an indication of the suitability of lamps for television scene lighting as does the Television Consistency Index itself. However, the correspondence between the behaviour of the Television Consistency Index under "daylight" reference conditions on the one hand, and the General Colour Rendering Index on the other, may not be as close as when the "studio" reference conditions are involved. Tests using a practical lamp (Lamp 5) having a spectral power distribution not too dissimilar to that of daylight appear to confirm this proposition. Furthermore, the General Colour Rendering Index gives no method of distinguishing between lamps compatible with studio lighting and those compatible with daylight, and in addition it involves "correlated colour temperature" in its derivation. The use of the General Colour Rendering Index is therefore not recommended.

(10) A field of work which has not so far been examined in detail is the relationship between average Television Consistency Index values taken over test colours representing the colour television reproduction gamut, average values taken over skin tone test colours, and the worst (numerically lowest) value found for individual test colours (see Section 2.1). Knowledge of the interrelations between these Index values would indicate the validity of quoting all three values (together with the identity of the test colour giving the worst value) in the complete expression of the Television Consistency Index, as is at present suggested. It might also lead to the formulation of a "one-value" Index, derived from the three separate Index values, which showed a higher degree of correlation with practical subjective test results than do any of the separate values themselves. The work so far carried out in this direction has given encouraging results for individual tests, but as the coefficients obtained in these "best-fitting" relationships have varied considerably according to the particular test under consideration, it has not been possible to suggest a suitable general relationship which could be used for this purpose.

Despite the small number of practical tests that have so far been carried out, the Television Consistency Index is recommended as a method of categorizing lamps in terms of their suitability as sources for television scene lighting. Calculation of a "General Television Consistency Index" using standardised parameters, with the spectral power distribution of the test illuminant as the only variable factor, is described in Appendix 1.

7. ACKNOWLEDGMENTS

As has been noted in the Foreword, the work described in this Report was carried out under the auspices of the CIE, at first through the Television Working Party of Sub-committee SC 3.2, and more recently through Technical Committee TC 1-11. The membership (part-time or full-time) of the original Television Working Party of SC 3.2 was as follows:-

Chairman: P.J. Darby, Independent Broadcasting Authority, U.K.

Secretary: E.W. Taylor, British Broadcasting Corporation, U.K.

Members: E. Barthès, Compagnie des Lampes, France.
A.N. Chalmers, University of Natal, South Africa.
Dr. H.D. Einhorn, Cape Town, South Africa.
T. Etbol, Danmarks Radio, Denmark.
B. Hisdal, Norsk Rikskringkasting, Norway.
Dr. G. Kawakami, Japan Color Research Institute, Japan.
C.E. Kern-Hansen, Danmarks Radio, Denmark.
Dr. H. Lang, Robert Bosch GmbH, W. Germany.
Leroy E. de Marsh, Eastman Kodak, U.S.A.
Drs. J.J. Opstelten, Philips, Netherlands.

Dr. B. Powell, Australian Broadcasting Corporation, Australia.
T. Saito, NHK, Japan.
Dr. U. Schultz, Fogra-Institut, W. Germany.
R. White, Television South Ltd. (formerly Thames Television Ltd), U.K.
Dr. T. Wintringham, U.S.A.

Advisory Members: Miss. M.B. Halstead, Thorn-EMI Lighting Ltd., U.K. (Chairman, TC 3.2).
Dr. C.J. Bartleson, U.S.A. (First Chairman, SC 3.2).
W.N. Sproson (formerly British Broadcasting Corporation), U.K. (Second Chairman, SC 3.2)

The membership of Technical Committee 1.11 as in July 1986 was:-

Chairman: W.N. Sproson*

Secretary: E.W. Taylor*

Members: Dr. A.N. Chalmers*
P.A. King, Independent Broadcasting Authority, U.K.
Dr. K. Kohmoto, Toshiba Corporation, Japan.
Dr. N. Ohta, Fuji Film Co. Ltd., Japan.
Drs. J.J. Opstelten*
Dr. B. Powell*
Dr. H. Terstiege, Bundesanstalt fur Materialprufung, W. Germany.
Dr. C.H.P. van Trigt, Philips, Netherlands.
R. White*

Advisory Members: Miss M.B. Halstead*
Dr. M.R. Pointer, Kodak Ltd., U.K.

In the above list an asterisk denotes a former member or advisory member of the Television Working Party.

The contributions made to the work by the members of the Technical Committee and by the members of the former Television Working Party are gratefully acknowledged, as is the permission given by the organizations to which individual members are affiliated for this work to be carried out. Thanks are particularly due to the following members, and their organizations, for their very significant contributions to the progress of the work:-

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Drs. J.J. Opstelten (Philips, Netherlands) for the provision of the spectral power distributions of the 63 "hypothetical" and 66 "practical" lamps used in the theoretical work on Television Consistency Index behaviour.

Dr. B. Powell (Australian Broadcasting Corporation) for computational work, particularly in deriving Television Consistency Index values for the large number of lamp, camera and test colour combinations used in the theoretical work, and in the statistical analysis of this data.

Mr. R. White (Television South Ltd. ; formerly with Thames Television Ltd.) for carrying out practical field trials while in his earlier post with Thames Television.

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APPENDIX 1

Data Required for Calculation of the General Television Consistency Index

Contents

First set of tables	:	test colour spectral reflectance data.
Second set of tables	:	reference camera and display data.
Third set of tables	:	spectral power distributions of reference illuminants.

Notes on Index calculation

The calculation of the General Television Consistency Index is carried out using the data contained in the tables in this Appendix. The calculation procedure may, however, be used with other data for special purposes, and the following outline of Index calculation is therefore given in general terms. The calculation may be considered in three stages:-

A) Calculation of display chromaticity and luminance for a particular test colour and scene illuminant.

B) Calculation of the Television Consistency Index for one test colour and one reference illuminant.

C) Calculation of the General Index values for sets of test colours and one or other reference illuminant.

A) Calculation of display chromaticity and luminance for a particular test colour and scene illuminant

(1) Calculation of camera-tube signals

Let R_c, G_c and B_c be the red, green and blue camera-tube signals for the test colour and scene illuminant under consideration. Then:-

$$R_c = \frac{\Sigma P(\lambda)\, S_R\,(\lambda)\, \rho\,(\lambda)}{0.6\ \Sigma P(\lambda)\, S_R\,(\lambda)}\ ;\ G_c = \frac{\Sigma P(\lambda)\, S_G\,(\lambda)\, \rho\,(\lambda)}{0.6\ \Sigma P(\lambda)\, S_G\,(\lambda)}\ ;\ B_c = \frac{\Sigma P(\lambda)\, S_B\,(\lambda)\, \rho\,(\lambda)}{0.6\ \Sigma P(\lambda)\, S_B\,(\lambda)}$$

where $P(\lambda)$ is the relative spectral power distribution of the illuminant

$\rho(\lambda)$ is the test colour spectral reflectance (see the first set of tables of this Appendix),

$S_R(\lambda)$, $S_G(\lambda)$,$S_B(\lambda)$ are respectively the camera analysis characteristics (spectral sensitivities) of the red, green and blue camera channels (see the second set of tables of this Appendix).

and the summations are taken at 5nm wavelength intervals from 380nm to 770nm inclusive.

The factor 0.6 is introduced in the denominators of the equations to take account of the assumed use of a 60% reflectance "white" when initially colour-balancing the camera.

(2) Calculation of the matrixed camera signals

Let R_m, G_m and B_m be the red, green and blue matrixed colour-camera signals for this test colour. Then:-

$$\begin{bmatrix} R_m \\ G_m \\ B_m \end{bmatrix} = [M_1] \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix}$$

where $[M_1]$ is the 3×3 "camera matrix" shown in the second set of tables of this Appendix.

(3) Inspection of signal-level values

It is essential that no matrixed colour-camera signal exceeds the "peak" value of unity. Accordingly, the calculations outlined in Sections 1 and 2 above are successively carried out for all members of the test colour set, and the complete set of matrixed signal values is then inspected. If one or more such values exceed unity, all the signal values are normalized so that the greatest value is equal to unity (see Section 3.5: note that, when using the test colours given in the first set of tables in this Appendix, the red matrixed camera signal for Test Colour 16 almost always exceeds unity and will be the one chosen for normalization).

(4) Calculation of display input signals

Returning to the procedure for signal-level calculations involving a particular test colour, let R_d, G_d and B_d be the red, green and blue display input signals for the test colour under consideration. Then:-

$$R_d = R_m^\gamma \; ; \; G_d = G_m^\gamma \; ; \; B_d = B_m^\gamma$$

where γ is the overall system transfer characteristic ("gamma") (see Section 2.3).

In the calculation of the General Television Consistency Index $\gamma = 1.2$.

(5) Calculations of displayed colour tristimulus values and chromaticity coordinates

Let X, Y, Z be the CIE tristimulus values for the displayed colour corresponding to the test colour under consideration. Then:-

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [M_2] \begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix}$$

where $[M_2]$ is the display matrix shown in the second set of tables of this Appendix.

The chromaticity coordinates (u', v') for the displayed colour are given[4] by

$$u' = \frac{4X}{X+15Y+3Z} \; ; \; v' = \frac{9Y}{X+15Y+3Z}$$

B) Calculation of the Television Consistency Index for one test colour and one reference illuminant

The calculations outlined in Section A above are carried out using successively the spectral power distribution of the test lamp and the spectral power distribution of one of the reference illuminants (the latter spd's are shown in the third set of tables of this Appendix). The Television Consistency Index for the particular test colour and reference illuminant under consideration (R_t) is then given by the successive application of the following Equations:-

$$L^*_T = 116\,(Y_T/Y_n)^{1/3} - 16 \qquad L^*_R = 116\,(Y_R/Y_n)^{1/3} - 16$$

$$u^*_T = 13L^*_T\,(u'_T - u'_n) \qquad u^*_R = 13L^*_R\,(u'_R - u'_n)$$

$$v^*_T = 13L^*_T\,(v'_T - v'_n) \qquad v^*_R = 13L^*_R\,(v'_R - v'_n)$$

$$\Delta L^* = L^*_T - L^*_R \qquad \Delta u^* = u^*_T - u^*_R \qquad \Delta v^* = v^*_T - v^*_R$$

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2}$$

$$R_t = 100 - 4.6\Delta E^*_{uv}$$

where subscripts T and R refer respectively to reproduction when using the test lamp and the reference illuminant,

and subscript n refers to the display white-point chromaticity (see the second set of tables of this Appendix).

C) Calculation of "general" Index values

(1) Calculations according to Sections A and B above are carried out successively for each test colour, using in turn first one and then the other reference illuminant.

(2) Considering first the results obtained using the P_{3000} reference illuminant, average or selection of individual Index values are taken as follows:-

i) The "overall" Index value is the average of the individual values found for the 18 test colours.

ii) The "skin tone" Index value is at present proposed (see Section 3.5, last paragraph) as the average of the individual values found for the first two test colours ("Dark Skin" and "Light Skin").

iii) The "worst" Index value is the algebraically lowest value found for any of the test colours.

iv) The test colour number for the worst Index value is also quoted.

(3) The same procedure as in Paragraph (2) above is carried out using the individual values found for the D_{65} reference illuminant.

(4) The two sets of Index values obtained from Paragraphs (2) and (3) above indicate the compatibility of the lamp with studio and daylight illumination respectively. In the future it may be possible to categorize the lamp as "studio compatible for television" or "daylight compatible for television" (see Section 6, paragraph (8)).

(5) The Index values are to be quoted to the nearest whole number. Nevertheless, calculations should be carried through to a higher accuracy: for example, an accuracy corresponding to two decimal places of Index value is convenient.

Appendix 1 (cont.). First Set of Tables: Test Colour Spectral Reflectance Data: Colours 1 — 4

Test Colour 1 (Dark skin)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.054	0.057	0.063	0.066
400	0.075	0.078	0.078	0.076	0.074	0.070	0.066	0.064	0.062	0.060
450	0.059	0.060	0.058	0.060	0.060	0.062	0.058	0.063	0.063	0.067
500	0.068	0.070	0.072	0.077	0.079	0.081	0.081	0.083	0.083	0.084
550	0.084	0.088	0.093	0.098	0.104	0.111	0.121	0.127	0.133	0.140
600	0.144	0.149	0.151	0.154	0.160	0.164	0.170	0.175	0.179	0.184
650	0.193	0.203	0.213	0.220	0.236	0.241	0.248	0.257	0.269	0.280
700	0.289	0.300	0.314	0.337	0.346	0.361	0.382	0.404	0.425	0.439
750	0.464	0.476	0.490	0.495	0.505					

Test Colour 2 (Light skin)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.092	0.109	0.134	0.161
400	0.186	0.200	0.205	0.206	0.207	0.209	0.211	0.213	0.216	0.221
450	0.227	0.237	0.246	0.259	0.273	0.285	0.294	0.304	0.305	0.309
500	0.314	0.323	0.334	0.340	0.332	0.316	0.300	0.292	0.290	0.295
550	0.300	0.302	0.297	0.295	0.304	0.328	0.365	0.409	0.450	0.488
600	0.520	0.540	0.556	0.566	0.574	0.582	0.593	0.602	0.607	0.625
650	0.631	0.639	0.655	0.661	0.687	0.693	0.711	0.722	0.737	0.757
700	0.768	0.786	0.798	0.815	0.822	0.823	0.835	0.845	0.855	0.848
750	0.862	0.861	0.868	0.868	0.826					

Test Colour 3 (Blue sky)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.105	0.127	0.164	0.213
400	0.271	0.314	0.333	0.344	0.345	0.344	0.346	0.346	0.347	0.343
450	0.337	0.333	0.327	0.324	0.319	0.306	0.290	0.288	0.280	0.274
500	0.265	0.258	0.250	0.240	0.229	0.220	0.212	0.207	0.203	0.198
550	0.193	0.191	0.187	0.181	0.174	0.170	0.167	0.162	0.158	0.161
600	0.156	0.152	0.150	0.145	0.142	0.137	0.133	0.132	0.126	0.127
650	0.121	0.118	0.115	0.115	0.112	0.110	0.110	0.109	0.108	0.108
700	0.106	0.105	0.105	0.106	0.106	0.105	0.107	0.105	0.106	0.105
750	0.108	0.107	0.110	0.110	0.102					

Test Colour 4 (Foliage)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.050	0.052	0.052	0.050
400	0.052	0.052	0.052	0.053	0.051	0.053	0.053	0.053	0.055	0.058
450	0.059	0.061	0.060	0.063	0.063	0.067	0.065	0.067	0.069	0.072
500	0.077	0.088	0.105	0.132	0.159	0.182	0.195	0.199	0.191	0.180
550	0.167	0.156	0.144	0.133	0.131	0.130	0.129	0.123	0.118	0.114
600	0.110	0.102	0.101	0.103	0.104	0.105	0.105	0.106	0.102	0.102
650	0.101	0.101	0.101	0.101	0.107	0.115	0.132	0.152	0.185	0.233
700	0.283	0.339	0.383	0.419	0.444	0.455	0.465	0.473	0.477	0.480
750	0.489	0.492	0.498	0.499	0.511					

Appendix 1 (cont.). First Set of Tables: Test Colour Spectral Reflectance Data: Colours 5 — 8

Test Colour 5 (Blue flower)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.101	0.127	0.170	0.233
400	0.310	0.373	0.409	0.424	0.432	0.437	0.437	0.438	0.437	0.432
450	0.428	0.423	0.417	0.412	0.405	0.395	0.380	0.373	0.364	0.355
500	0.342	0.333	0.316	0.296	0.267	0.245	0.227	0.212	0.206	0.203
550	0.203	0.204	0.196	0.190	0.190	0.194	0.201	0.210	0.216	0.225
600	0.228	0.232	0.238	0.240	0.236	0.236	0.240	0.248	0.261	0.289
650	0.322	0.362	0.407	0.446	0.488	0.512	0.546	0.546	0.555	0.563
700	0.564	0.575	0.578	0.586	0.590	0.589	0.601	0.604	0.606	0.605
750	0.614	0.616	0.617	0.617	0.614					

Test Colour 6 (Bluish green)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.108	0.132	0.168	0.213
400	0.260	0.292	0.308	0.317	0.320	0.328	0.336	0.342	0.352	0.360
450	0.371	0.386	0.405	0.433	0.465	0.497	0.528	0.557	0.576	0.591
500	0.586	0.591	0.586	0.582	0.567	0.559	0.545	0.533	0.512	0.492
550	0.472	0.449	0.429	0.402	0.380	0.355	0.332	0.309	0.284	0.262
600	0.247	0.233	0.224	0.217	0.212	0.209	0.207	0.205	0.200	0.198
650	0.199	0.197	0.199	0.203	0.210	0.216	0.218	0.226	0.232	0.236
700	0.238	0.242	0.242	0.239	0.232	0.227	0.229	0.230	0.237	0.248
750	0.256	0.269	0.274	0.278	0.274					

Test Colour 7 (Orange)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.052	0.054	0.052	0.050
400	0.052	0.052	0.052	0.051	0.050	0.050	0.052	0.050	0.051	0.051
450	0.052	0.051	0.051	0.053	0.053	0.054	0.055	0.056	0.055	0.058
500	0.061	0.063	0.068	0.077	0.086	0.098	0.120	0.145	0.175	0.206
550	0.236	0.270	0.302	0.341	0.375	0.410	0.440	0.467	0.488	0.509
600	0.518	0.532	0.540	0.551	0.557	0.562	0.568	0.575	0.581	0.584
650	0.585	0.590	0.601	0.596	0.600	0.596	0.604	0.603	0.606	0.607
700	0.608	0.615	0.617	0.621	0.622	0.619	0.625	0.628	0.630	0.627
750	0.635	0.639	0.640	0.640	0.641					

Test Colour 8 (Purplish blue)

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.094	0.113	0.141	0.186
400	0.235	0.275	0.297	0.316	0.317	0.333	0.346	0.355	0.368	0.378
450	0.381	0.377	0.368	0.356	0.340	0.322	0.296	0.269	0.241	0.220
500	0.197	0.182	0.166	0.151	0.138	0.127	0.120	0.115	0.108	0.104
550	0.101	0.095	0.090	0.084	0.082	0.081	0.081	0.081	0.081	0.083
600	0.083	0.080	0.079	0.080	0.081	0.081	0.084	0.089	0.092	0.096
650	0.103	0.107	0.112	0.111	0.112	0.109	0.104	0.102	0.099	0.099
700	0.100	0.100	0.103	0.106	0.109	0.113	0.122	0.127	0.138	0.153
750	0.173	0.193	0.215	0.241	0.249					

Appendix 1 (cont.). First Set of Tables: Test Colour Spectral Reflectance Data: Colours 9 — 12

Test Colour 9 (Moderate red)

λ + → (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.088	0.102	0.121	0.136
400	0.151	0.153	0.151	0.144	0.142	0.141	0.139	0.135	0.136	0.135
450	0.133	0.132	0.129	0.130	0.129	0.127	0.121	0.118	0.109	0.105
500	0.105	0.104	0.101	0.100	0.094	0.091	0.089	0.092	0.095	0.097
550	0.104	0.109	0.111	0.113	0.116	0.134	0.167	0.223	0.291	0.362
600	0.426	0.474	0.511	0.537	0.551	0.562	0.565	0.570	0.575	0.574
650	0.579	0.577	0.579	0.577	0.580	0.581	0.579	0.581	0.581	0.583
700	0.581	0.581	0.580	0.586	0.585	0.584	0.589	0.587	0.590	0.582
750	0.589	0.592	0.590	0.590	0.600					

Test Colour 10 (Purple)

λ + → (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.083	0.100	0.125	0.154
400	0.183	0.198	0.206	0.207	0.207	0.201	0.194	0.184	0.175	0.163
450	0.154	0.142	0.129	0.120	0.109	0.102	0.095	0.090	0.081	0.077
500	0.070	0.067	0.065	0.063	0.059	0.058	0.056	0.053	0.052	0.052
550	0.051	0.053	0.055	0.056	0.054	0.052	0.053	0.049	0.051	0.055
600	0.058	0.063	0.073	0.087	0.103	0.120	0.137	0.149	0.161	0.175
650	0.188	0.197	0.208	0.218	0.229	0.241	0.249	0.262	0.272	0.284
700	0.292	0.304	0.312	0.325	0.329	0.333	0.343	0.346	0.350	0.350
750	0.359	0.360	0.362	0.369	0.361					

Test Colour 11 (Yellow green)

λ + → (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.045	0.048	0.050	0.050
400	0.054	0.053	0.053	0.055	0.053	0.057	0.059	0.059	0.062	0.065
450	0.070	0.075	0.081	0.092	0.102	0.116	0.136	0.158	0.185	0.225
500	0.274	0.328	0.390	0.446	0.485	0.511	0.529	0.538	0.539	0.535
550	0.526	0.521	0.511	0.500	0.484	0.467	0.450	0.435	0.412	0.395
600	0.377	0.363	0.352	0.346	0.339	0.337	0.337	0.331	0.326	0.322
650	0.323	0.320	0.325	0.327	0.334	0.340	0.347	0.355	0.362	0.369
700	0.373	0.376	0.375	0.379	0.372	0.365	0.367	0.375	0.379	0.388
750	0.403	0.415	0.430	0.430	0.447					

Test Colour 12 (Orange yellow)

λ + → (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.049	0.052	0.054	0.055
400	0.054	0.057	0.057	0.059	0.057	0.057	0.059	0.057	0.058	0.060
450	0.061	0.061	0.062	0.067	0.072	0.081	0.088	0.098	0.106	0.112
500	0.120	0.130	0.143	0.163	0.188	0.218	0.256	0.304	0.351	0.399
550	0.442	0.476	0.505	0.532	0.544	0.561	0.579	0.539	0.597	0.604
600	0.617	0.617	0.618	0.624	0.625	0.630	0.647	0.635	0.638	0.642
650	0.649	0.650	0.649	0.650	0.677	0.657	0.653	0.659	0.658	0.662
700	0.661	0.666	0.668	0.672	0.671	0.667	0.677	0.678	0.682	0.678
750	0.686	0.693	0.690	0.700	0.710					

Appendix 1 (cont.). First Set of Tables: Test Colour Spectral Reflectance Data: Colours 13 — 16

Test Colour 13 (Blue)

λ (nm) ↓ +→	0	5	10	15	20	25	30	35	40	45
350							0.068	0.084	0.104	0.127
400	0.156	0.178	0.194	0.209	0.221	0.234	0.250	0.264	0.287	0.308
450	0.318	0.323	0.317	0.303	0.276	2.255	0.225	0.193	0.160	0.139
500	0.117	0.104	0.087	0.077	0.066	0.060	0.056	0.053	0.050	0.047
550	0.045	0.042	0.043	0.040	0.040	0.038	0.038	0.037	0.036	0.037
600	0.038	0.036	0.037	0.037	0.037	0.039	0.039	0.042	0.040	0.042
650	0.044	0.045	0.047	0.048	0.050	0.048	0.046	0.050	0.048	0.051
700	0.049	0.052	0.054	0.057	0.060	0.065	0.069	0.076	0.087	0.102
750	0.123	0.147	0.174	0.201	0.224					

Test Colour 14 (Green)

λ (nm) ↓ +→	0	5	10	15	20	25	30	35	40	45
350							0.045	0.048	0.054	0.054
400	0.057	0.059	0.060	0.060	0.060	0.062	0.064	0.064	0.069	0.070
450	0.075	0.079	0.083	0.090	0.099	0.109	0.120	0.132	0.144	0.158
500	0.175	0.196	0.231	0.272	0.307	0.338	0.352	0.357	0.353	0.341
550	0.323	0.305	0.286	0.265	0.244	0.224	0.203	0.180	0.161	0.144
600	0.124	0.108	0.098	0.089	0.084	0.080	0.076	0.075	0.071	0.071
650	0.070	0.067	0.067	0.067	0.068	0.070	0.070	0.074	0.076	0.079
700	0.080	0.082	0.086	0.085	0.083	0.081	0.081	0.081	0.083	0.086
750	0.091	0.094	0.098	0.101	0.103					

Test Colour 15 (Red)

λ (nm) ↓ +→	0	5	10	15	20	25	30	35	40	45
350							0.043	0.045	0.046	0.045
400	0.047	0.046	0.048	0.046	0.046	0.046	0.048	0.044	0.046	0.047
450	0.047	0.047	0.046	0.046	0.044	0.044	0.040	0.042	0.039	0.040
500	0.040	0.039	0.040	0.040	0.038	0.038	0.039	0.038	0.040	0.040
550	0.041	0.042	0.044	0.046	0.047	0.054	0.064	0.081	0.112	0.156
600	0.216	0.283	0.358	0.434	0.499	0.549	0.585	0.607	0.624	0.633
650	0.650	0.652	0.652	0.656	0.661	0.666	0.664	0.671	0.671	0.677
700	0.673	0.678	0.680	0.689	0.688	0.685	0.691	0.694	0.696	0.692
750	0.698	0.704	0.700	0.699	0.708					

Test Colour 16 (Yellow)

λ (nm) ↓ +→	0	5	10	15	20	25	30	35	40	45
350							0.047	0.047	0.048	0.047
400	0.050	0.052	0.052	0.051	0.051	0.053	0.053	0.053	0.057	0.056
450	0.058	0.060	0.062	0.067	0.076	0.090	0.109	0.142	0.183	0.228
500	0.274	0.319	0.360	0.405	0.443	0.475	0.510	0.544	0.571	0.594
550	0.612	0.630	0.646	0.656	0.668	0.677	0.691	0.696	0.701	0.702
600	0.729	0.701	0.704	0.707	0.708	0.713	0.721	0.716	0.717	0.718
650	0.726	0.729	0.730	0.728	0.747	0.739	0.737	0.743	0.740	0.756
700	0.742	0.749	0.751	0.753	0.754	0.750	0.760	0.762	0.769	0.762
750	0.774	0.776	0.779	0.784	0.784					

Appendix 1 (cont.). First Set of Tables: Test Colour Spectral Reflectance Data: Colours 17 — 18

Test Colour 17 (Magenta)

λ + → (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.106	0.129	0.168	0.229
400	0.297	0.346	0.367	0.372	0.377	0.373	0.362	0.351	0.340	0.323
450	0.306	0.293	0.276	0.259	0.250	0.234	0.220	0.206	0.190	0.179
500	0.169	0.163	0.152	0.140	0.126	0.113	0.104	0.098	0.098	0.102
550	0.104	0.103	0.104	0.103	0.106	0.118	0.140	0.170	0.212	0.257
600	0.313	0.354	0.403	0.457	0.501	0.546	0.587	0.612	0.637	0.655
650	0.677	0.684	0.693	0.695	0.714	0.710	0.720	0.715	0.714	0.739
700	0.719	0.726	0.728	0.733	0.737	0.732	0.743	0.742	0.748	0.741
750	0.753	0.754	0.761	0.758	0.759					

Test Colour 18 (Cyan)

λ + → (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							0.085	0.102	0.130	0.163
400	0.201	0.228	0.247	0.254	0.262	0.278	0.282	0.300	0.319	0.332
450	0.348	0.363	0.382	0.401	0.419	0.431	0.438	0.441	0.438	0.429
500	0.415	0.404	0.381	0.358	0.339	0.316	0.288	0.262	0.236	0.210
550	0.186	0.162	0.142	0.129	0.116	0.105	0.099	0.092	0.088	0.086
600	0.081	0.077	0.078	0.076	0.076	0.076	0.076	0.076	0.076	0.077
650	0.078	0.077	0.081	0.080	0.081	0.079	0.079	0.079	0.077	0.076
700	0.075	0.074	0.074	0.076	0.077	0.081	0.084	0.090	0.098	0.111
750	0.130	0.151	0.179	0.195	0.204					

Appendix 1 (cont.). Second Set of Tables: Reference Camera and Display Data

Camera analysis characteristics (spectral sensitivity): Red channel

λ (nm) ↓ / + →	0	5	10	15	20	25	30	35	40	45
350							0	0	0	0
400	0	0	0	0	0	0	0	0	0	0
450	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0	0	5.8	11.4	18.0
550	24.3	31.2	38.5	46.2	54.6	63.7	73.1	82.7	91.1	97.0
600	100.0	99.0	95.1	88.5	79.9	69.6	58.8	49.0	39.8	31.6
650	24.5	18.6	13.8	10.0	7.1	5.1	3.6	2.5	1.8	1.2
700	0.8	0.6	0.4	0.3	0.3	0.2	0.1	0	0	0
750	0	0	0	0	0					

Camera analysis characteristics (spectral sensitivity): Green channel

λ (nm) ↓ / + →	0	5	10	15	20	25	30	35	40	45
350							0	0	0	0
400	0	0	0	0	0	0	0	0	0	0
450	0	0	0	0.5	2.4	7.3	13.4	19.0	25.1	32.3
500	40.7	51.2	62.5	74.0	84.3	91.7	96.7	99.5	100.0	98.3
550	93.8	85.3	75.0	64.6	54.6	46.2	38.8	32.3	26.4	20.9
600	15.8	10.8	6.4	2.7	0.2	0	0	0	0	0
650	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0
750	0	0	0	0	0					

Camera analysis characteristics (spectral sensitivity): Blue channel

λ (nm) ↓ / + →	0	5	10	15	20	25	30	35	40	45
350							0	0.4	1.1	2.0
400	3.8	6.1	11.3	22.2	37.2	58.4	78.3	88.6	94.4	98.6
450	100.0	98.6	93.8	84.3	72.0	57.8	43.9	32.6	23.6	18.0
500	14.1	10.8	8.0	5.2	2.9	1.2	0.1	0	0	0
550	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0	0	0	0
650	0	0	0	0	0	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0
750	0	0	0	0	0					

Appendix 1 (cont.).

Camera matrix

$$\begin{bmatrix} R_m \\ G_m \\ B_m \end{bmatrix} = \begin{bmatrix} 1.138 & -0.175 & 0.037 \\ -0.112 & 1.151 & -0.039 \\ 0.000 & -0.091 & 1.091 \end{bmatrix} \cdot \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix}$$

Subscripts m and c denote matrixed and camera-tube signals respectively (see Notes on Index calculation, paragraphs A(2) and A(1)).

Display matrix[10]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4306 & 0.3415 & 0.1784 \\ 0.2220 & 0.7067 & 0.0713 \\ 0.0202 & 0.1295 & 0.9394 \end{bmatrix} \cdot \begin{bmatrix} R_d \\ G_d \\ B_d \end{bmatrix}$$

Subscript d denotes display input signals (see Notes on Index calculation, paragraphs A(4) and A(5)). Note that the precise values of these coefficients depend on the chromaticity coordinates selected for the white point. In the present case $x = 0.3127$, $y = 0.3290$ and $z = 0.3583$, giving $u' = 0.19783$, $v' = 0.46832$.

Third Set of Tables: Spectral Power Distributions of Reference Illuminants

Studio reference: Illuminant P_{3000}

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							12.03	13.27	14.60	16.00
400	17.49	19.06	20.71	22.44	24.26	26.15	28.12	30.17	32.30	34.50
450	36.78	39.13	41.54	44.03	46.58	49.18	51.85	54.58	57.35	60.18
500	63.05	65.97	68.93	71.92	74.95	78.01	81.10	84.21	87.34	90.48
550	93.65	96.82	100.00	103.19	106.37	109.56	112.74	115.92	119.08	122.24
600	125.37	128.50	131.60	134.68	137.73	140.76	143.76	146.73	149.67	152.57
650	155.44	158.27	161.06	163.81	166.52	169.19	171.81	174.39	176.92	179.41
700	181.85	184.24	186.58	188.87	191.11	193.30	195.44	197.53	199.57	201.55
750	203.48	205.36	207.19	208.97	210.69					

($c_2 = 1.4388$).

Daylight reference: Illuminant D_{65}

λ +→ (nm) ↓	0	5	10	15	20	25	30	35	40	45
350							50.0	52.3	54.6	68.7
400	82.8	87.2	91.5	92.4	93.4	90.0	86.7	95.8	104.9	111.0
450	117.0	117.4	117.8	116.4	114.9	115.4	115.9	112.4	108.8	109.1
500	109.4	108.6	107.8	106.3	104.8	106.2	107.7	106.0	104.4	104.2
550	104.0	102.0	100.0	98.2	96.3	96.0	95.8	92.2	88.7	89.4
600	90.0	89.8	89.6	88.6	87.7	85.0	83.3	83.5	83.7	81.8
650	80.0	80.1	80.2	81.2	82.3	80.3	78.3	74.0	69.7	70.6
700	71.6	73.0	74.3	68.0	61.6	65.8	69.9	72.5	75.1	69.4
750	63.6	55.0	46.4	56.6	66.8					

APPENDIX 2

Individual and Mean Subjective Grades obtained in Practical Field Trials

Trial 1: P_{3000} Reference

Observer	Lamp 1		Lamp 2		Lamp 3		Lamp 4		Lamp 5		Lamp 6		Lamp 7		Lamp 8	
	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S
1	3	3	3	3	2	2	4	4	3	3	2	3	3	3	2	3
2	3	2	3	2	2	2	4	4	4	4	3	3	3	3	2	3
3	3	3	3	3	2	2	4	4	4	4	3	3	4	3	3	3
4	3	2	1	1	1	1	5	3	3	2	2	2	3	3	1	2
5	2	3	1	3	1	1	4	4	3	4	3	4	2	4	3	3
6	3	3	4	3	1	2	4	4	3	4	2	3	3	3	3	3
7	2	3	3	3	4	3	5	4	3	3	3	3	5	3	4	3
8	2	2	3	2	1	2	4	4	3	3	3	3	4	2	3	3
9	3	2	4	3	2	2	5	4	4	3	2	3	4	2	3	3
10	3	2	3	2	2	2	5	4	3	3	2	3	4	3	3	3
11	3	2	4	2	2	1	5	4	3	3	3	3	2	3	3	3
12	3	2	3	2	1	1	4	4	4	3	2	3	2	3	2	3
13	3	2	4	2	2	1	4	3	4	3	3	2	3	2	3	2
14	3	3	3	2	2	2	4	3	3	3	3	3	2	3	2	3
15	3	3	2	2	1	1	5	4	4	4	2	3	2	3	2	3
16	3	4	4	3	3	2	4	4	4	3	3	4	3	3	3	4
17	2	3	2	3	2	2	3	3	2	2	2	2	2	2	2	2
18	4	2	3	2	2	2	3	4	4	4	3	4	3	4	4	4
19	4	2	4	2	2	1	4	3	2	3	2	2	4	2	2	3
20	2	3	3	3	3	3	4	4	5	3	4	3	4	4	4	3
21	3	2	3	3	1	2	5	5	3	3	2	3	4	2	2	4
22	4	3	3	3	2	3	5	5	4	4	3	4	4	3	3	4
23	3	2	4	2	1	1	5	3	3	3	1	2	5	1	2	3
24	2	2	4	2	1	1	5	4	3	3	2	2	4	2	2	3
25	2	2	4	2	1	2	5	3	2	3	2	2	4	2	2	3
26	3	2	4	2	1	2	5	4	2	3	3	3	3	4	2	3
27	3	2	4	2	1	1	5	5	3	4	3	3	4	2	3	3
28	2	2	4	3	1	2	5	4	2	3	3	3	4	3	4	4
29	3	3	4	3	1	2	5	3	3	3	2	3	4	3	2	4
30	3	2	4	2	1	2	4	4	4	4	2	4	3	3	2	4
31	2	2	4	2	1	1	5	4	2	3	2	3	4	3	1	3
32	2	3	3	3	1	3	4	3	2	4	1	3	3	3	1	4
33	2	2	3	1	1	1	4	4	3	3	2	4	3	3	2	4
34	3	3	2	2	1	1	5	5	2	4	2	4	5	4	2	4
35	2	2	2	2	1	1	5	4	4	3	2	3	4	2	3	2
36	3	2	3	3	1	2	5	4	3	3	2	3	4	2	2	3
37	3	2	3	3	1	2	5	4	3	3	2	3	3	3	2	3
Mean	2.76	2.41	3.19	2.38	1.51	1.73	4.49	3.86	3.14	3.24	2.38	3.00	3.43	2.78	2.46	3.16

1 Very poor consistency
2 Poor consistency
3 Moderate consistency
4 Good consistency
5 Excellent consistency

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Appendix 2 (cont.). Individual and Mean Subjective Grades obtained in Practical Field Trials

Trial 2: P_{3000} Reference

Observer	Lamp 1	Lamp 2	Lamp 3	Lamp 4	Lamp 5	Lamp 6	Lamp 7	Lamp 8	Lamp 9
1	2	2	2	2	1	2	3	3	4
2	2	2	3	3	2	3	3	4	5
3	3	4	2	4	2	3	4	4	4
4	1	2	1	4	1	4	4	3	5
5	3	4	2	3	3	4	4	4	5
6	2	2	2	3	2	3	3	2	4
7	2	2	2	4	3	3	3	3	4
8	2	2	1	3	2	3	3	3	4
9	2	3	1	4	3	3	4	3	5
10	1	2	2	4	2	3	4	4	5
11	2	2	1	3	3	2	2	2	3
12	3	4	3	1	3	2	4	4	3
13	2	2	1	4	2	3	4	3	3
14	1	2	1	4	3	3	4	4	4
15	2	2	1	4	2	3	2	4	4
16	2	2	1	3	2	3	4	3	2
17	2	3	2	3	4	3	4	3	4
18	1	3	1	3	2	4	4	4	4
19	2	3	2	4	3	3	4	3	5
20	1	3	1	4	2	3	4	2	5
21	1	3	2	4	4	4	4	3	4
22	1	3	2	4	2	3	3	3	4
23	1	3	1	4	2	3	3	3	4
24	1	2	1	4	2	4	3	3	4
25	2	3	2	5	2	4	4	3	5
26	2	3	1	4	2	4	3	3	4
27	2	3	2	4	2	4	3	3	4
Mean	1.78	2.63	1.59	3.56	2.33	3.18	3.48	3.18	4.11

1 Very poor consistency
2 Poor consistency
3 Moderate consistency
4 Good consistency
5 Excellent consistency

Alternate presentation only

Appendix 2 (cont.). Individual and Mean Subjective Grades obtained in Practical Field Trials

Trial 3: "Lamp 5" Reference

Observer	Lamp 1		Lamp 2		Lamp 3		Lamp 4		Lamp 5		Lamp 6		Lamp 7		Lamp 8		Lamp 9	
	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S
1	2	3	2	2	1	1	3	3	4	4	3	3	2	3	3	3	2	2
2	3	4	2	3	2	1	4	3	5	4	3	2	3	3	4	4	3	2
3	3	3	2	3	1	1	4	2	5	4	3	2	4	2	4	3	2	2
4	3	4	3	4	2	2	4	3	4	4	2	2	3	3	3	4	2	2
5	2	3	3	3	1	1	4	4	4	4	4	3	4	3	3	4	3	3
6	3	4	3	3	2	2	4	4	5	5	2	3	2	3	5	3	3	1
7	4	3	3	3	1	1	4	3	3	3	2	2	3	2	2	2	2	1
8	3	2	2	2	1	1	4	3	4	4	3	2	4	3	5	3	1	1
9	3	3	2	3	1	2	4	4	5	5	2	3	2	2	3	4	2	2
10	4	4	3	3	1	2	4	4	5	4	3	3	3	4	4	4	3	3
11	3	4	3	3	1	1	4	4	5	5	4	4	3	2	3	4	2	2
12	3	2	2	3	1	1	4	3	4	5	2	2	2	2	4	3	2	1
13	3	3	3	3	2	2	4	3	4	4	3	3	4	3	4	3	3	2
14	2	2	4	4	2	2	5	4	5	5	3	3	4	3	4	5	3	4
15	3	4	2	4	1	3	3	3	5	5	2	2	3	3	4	4	2	2
16	4	3	3	2	2	1	3	4	5	5	5	2	4	3	4	4	3	3
17	4	4	3	4	1	2	3	2	5	3	2	1	2	1	5	3	3	1
18	3	3	2	2	1	3	3	2	5	5	2	4	2	2	3	3	2	1
Mean	3.06	3.22	2.61	3.00	1.33	1.61	3.78	3.22	4.56	4.33	2.78	2.56	3.00	2.61	3.72	3.50	2.39	1.94

1 Very poor consistency
2 Poor consistency
3 Moderate consistency
4 Good consistency
5 Excellent consistency

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